MASSACHUSETTS WATER RESOURCES COMMISSION

Groundwater & Groundwater Law in Massachusetts

Massachusetts
Division of Water Resources

1976

MASSACHUSETTS • WATER RESOURCES COMMISSION •

DIVISION OF WATER RESOURCES

This publication resulted from a study authorized by the Massachusetts General Court pursuant to Chapter 111 of the Resolves of 1973. Believing the report submitted to the Legislature to be of considerable public interest, the Massachusetts Water Resources Commission has authorized its printing and distribution.

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Introduction

Background of Report: This study was undertaken in accordance with Chapter III of the Resolves of 1973, enacted August 20, 1973, by the Senate and House of Representatives and approved by the Governor on August 23, 1973:

> RESOLVE DIRECTING THE WATER RESOURCES COMMISSION TO CONDUCT AN INVESTIGATION AND STUDY OF THE PHYSICAL RELATIONSHIPS BETWEEN GROUND AND SURFACE WATER; AND THE INTERRELATED EFFECTS OF MAN'S ACTIVITIES ON GROUND AND SURFACE WATERS OF THE COMMONWEALTH?
>
> RESOLVED, That the water resources commission is hereby authorized and directed to make an investigation and study relative to the physical relationship between ground and surface water; and to the interrelated effects of man's activities on ground and surface waters. Said commission shall also consider the effect of altering surficial conditions, the existing and potential effects of ground water withdrawal, the disposition of wastes and the regulatory measures regarding ground and surface waters employed in the commonwealth as compared with such regulatory measures employed in other jurisdictions. Said commission shall report to the general court the results of its investigation and study and its recommendations, if any, together with drafts of legislation necessary to carry its recommendations into effect, by filing the same with the clerk of the house of representatives on or before February first, nineteen hundred and seventy-four.

An extension of the completion date was granted in Chapter 13 of the Resolves of 1974, enacted May 20, 1974, by the Senate and House of Representatives and approved by the governor on May 30, 1974:

> RESOLVE CONTINUING THE INVESTIGATION AND STUDY BY THE WATER RESOURCES COMMISSION OF THE PHYSICAL RELATIONSHIPS BETWEEN GROUND AND SURFACE WATERS AND THE INTERRELATED EFFECTS OF MAN'S ACTIVITIES ON GROUND AND SURFACE WATERS OF THE COMMONWEALTH.
>
> RESOLVED, That the water resources commission is hereby authorized and directed to continue its investigation and study authorized by chapter one hundred and eleven of the resolves of nineteen hundred and seventy-three. Said commission shall file its final report not later than July first, nineteen hundred and seventy-four.

Purpose and Scope; The Water Resources Commission, consisting of representatives of the Department of Natural resources(Chair), the Department of Public Health, the Department of Public Works, the Metropolitan District Commission, the Division of Fisheries and Game, the Department of Commerce and Development, the Department of Agriculture and four citizen appointees; delegated to the Division of Water Resources of the Water Resources Commission primary responsibility for conducting the study and preparing the report. The Division of Water Resources, recognizing the constraints of time imposed by the date for filing its report with the legislature, created an ad hoc committee of citizens with interdisciplinary professional backgrounds covering the fields of hydrology, civil engineering, biology, economics, medicine and law to furnish information and submit recommendations relevant to this report.

The Division of Water Resources and the citizen task force agreed that the report should serve the following purposes:

1. To explain in non-technical language the interrelationship of groundwater and surface water so that the report might serve as a convenient, reliable reference for individuals who are not specialists in water resources, giving particular emphasis to conditions existing in the Commonwealth of Massachusetts.

2. To describe, as explicitly and concisely as possible, existing and potential problems of groundwater resources with an adverse effect upon water quantity or water quality, which are caused by man's activities, using representative case studies to illustrate the problems.

3. To present the economic and legal factors influencing the solution to problems of water quality and water quantity.

4. To discuss alternatives designed to protect the water resources of the Commonwealth, to minimize the dangers to public health and to reduce the number and magnitude of water-related problems.

5. To draft legislation and regulations, if appropriate.

Participants in the Study; The following individuals contributed to the preparation of this report:

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The activities of the Citizen Task Force were made possible in part by financial support from the Massachusetts Audubon Society.

Description of Study Area

In order to understand the interrelationship of ground and surface waters in Massachusetts, it is important to be familiar with the geographical characteristics of the state, especially its topography, climate, population distribution, drainage basins and the special hydrologic problems of a coastal region.

Climate: Average annual precipitation ranges from 40 to 50 inches per year, with the Coastal division (the driest) receiving only about two inches of precipitation less than the Western division (the wettest). Massachusetts, one of the relatively few areas of the world that does not have "rainy" and "dry" seasons, is fortunate in having its precipitation rather evenly distributed throughout the year. Precipitation in the form of snow increases rapidly from the coast westward, with Cape Cod receiving annually an average of about 25 to 30 inches while the western part of the state records up to 60 to 80 inches.

Flooding occurs most frequently in the spring, caused by a combination of rain and melting snow, but some of the most severe floods recorded have been those associated with hurricanes or storms of tropical origin in late summer or fall, normally the low water season. Severe floods in the more recent years have occurred in Massachusetts in November 1927, March 1936, July and September 1938, December 1948, August and October 1955, and March 1968.

Population Distribution: According to the 1970 census, the total population of Massachusetts was 5,689,170, with an average density for the entire state of 726 persons per square mile.

A large proportion (82.5%) of this population occupies only 38.4 percent of the land in the state and has an average population density of slightly more than 1,560 person per square mile, if Standard Metropolitan Statistical Areas (SMSA) are used as the basis for classifying urbanized areas. Using the SMSA categories, the Boston area has the highest population density (2,786 persons per square mile) which is almost five times greater than that of Pittsfield, which has an SMSA density of 572 persons per square mile.

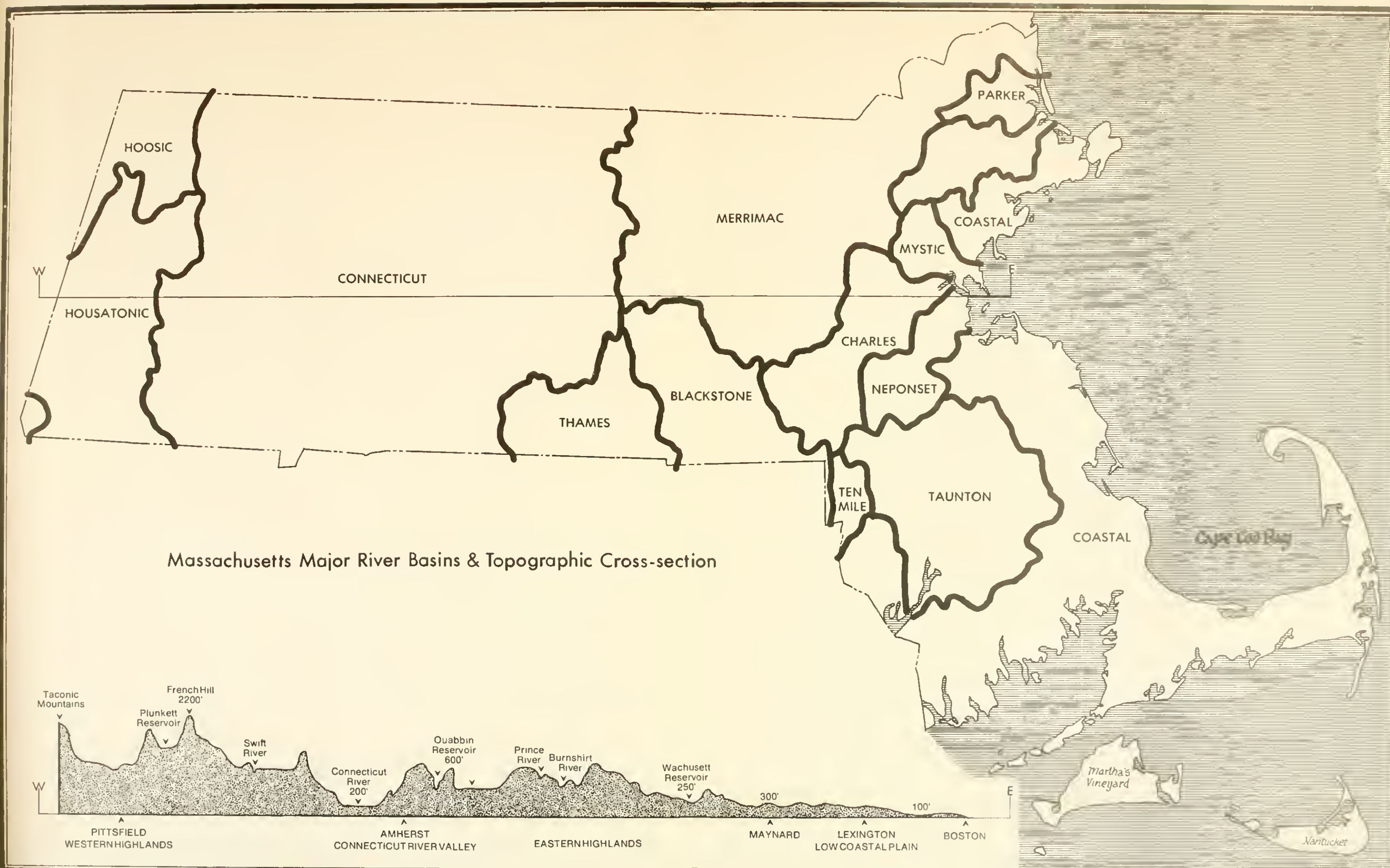
The concentration of the state's population in urban areas and the concentration of the state's urban population in the four counties encompassing the metropolitan Boston region is significant to a study of the water resources of the Commonwealth. In spite of abundant water resources for the state as a whole, this concentration of population creates special problems, such as (1) distribution of the available water supply, and (2) loss of potential water supplies due to increasing urbanization.

Major Drainage Basins: Of the major inter-state river basins in the Commonwealth, in only two instances is the Massachusetts portion of the basin located downstream from a substantial portion of the watershed; these two are the Connecticut and the Merrimack Rivers. The five other principal interstate rivers have their head-waters in Massachusetts and flow southerly into Connecticut or Rhode Island. All other river basins lie completely within Massachusetts.

Drainage basins (watershed areas) are the most natural units for managing water resources, both surface water and groundwater; for observing the stream network comprising a basin; and for determining the effects of water pollution, floods and flood control projects, or the withdrawal of water for municipal and industrial purposes. They are important in three areas of general concern today: (1) location of new sources for municipal water supplies, (2) sites for the disposal of solid wastes, and (3) areas suitable for the disposition of sewage wastes. In spite of these facts, not many of us are even familiar with the watershed where we live or work.

Hydrologic Problems of Coastal Regions: Cape Cod, Martha's Vineyard, Nantucket and the Elizabeth Islands, with a total area of 398,464 acres (622.6 square miles), have such different hydrologic characteristics from the rest of Massachusetts that for the purposes of this report it is worth grouping them into a distinct category, which we call "Coastal". The rest of the state, except for the small strip of land bordering the coastline from New Hampshire to Rhode Island, therefore, may be regarded as non-coastal.

The principal features of the Coastal subdivision are: (1) its dependence upon groundwater supplies, and (2) its proximity to salt water. Cape Cod and the Islands are composed almost entirely of unconsolidated deposits of glacial origin overlying bedrock. Depth of the underlying bedrock ranges from 80 to 160 feet below sea level in the Bourne-Sandwich area near the Cape Cod Canal, dropping to a level of 300 to 500 feet below sea level under most of the Cape and adjoining bays. The entire Cape must be treated as one continuous drainage area without underlying topography which might serve as a drainage divide. The Cape is also a region of very low surface relief, with no highlands to serve as collecting regions and no integrated network of streams to furnish a supply of fresh water. The surface elevation of most ponds serves as an indication of the height of the water table above sea level. The only source of fresh water is from groundwater supplies; the only source of replenishment for groundwater supplies is the annual precipitation falling on the surface of the Coastal region.



Massachusetts Major River Basins & Topographic Cross-section

Groundwater Primer

This section, dealing as it does with hydrologic concepts and terms, is specifically designed for non-specialists so that they will have a better understanding of the cases presented in the succeeding sections of this report.

The Hydrologic Cycle: There are two aspects to the hydrologic cycle: one is the familiar, visible circulation of water involving evaporation, precipitation and flow through a surface drainage network of lakes and streams; the other part of the cycle deals with the subsurface movement of water through the ground. The first is an observable phenomenon of the natural world; the second can only be inferred through analysis of water table fluctuation, base streamflow and other empirical hydrologic data. (See Figure 3-1.)

Since this report deals with the interrelationship between ground and surface water, it will only briefly describe the visible portion of the cycle but deal extensively with the circulation of groundwater and surface water. One of the principal objectives of this report is to explain the factors determining the conversion of surface water into groundwater and groundwater into surface water.

Energy: Energy from the sun provides the motive force in the hydrologic cycle; wind patterns determine the distribution of moisture on the surface of the earth; and the earth's gravitational field causes flow within the terrestrial part of the system, causing water to flow from points of higher elevation to points of lower elevation, with sea level acting as the ultimate base level.

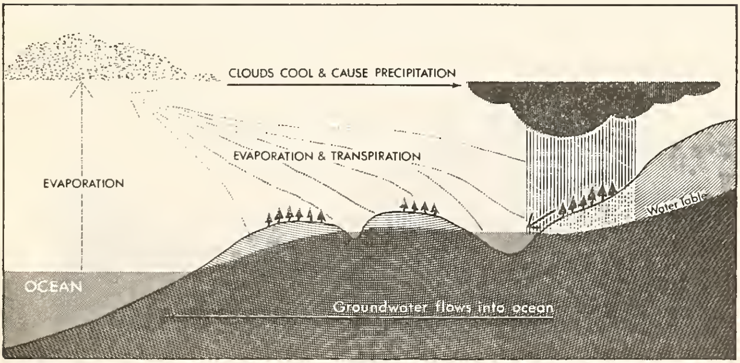


Figure 3-1

The Hydrologic Cycle

Atmospheric Phase: Evaporation, driven by solar energy, is the upward movement of water from the earth to the atmosphere and is the process by which liquid or solid water is changed to a gaseous (vapor) form It is influenced by the amount of heat from the sun reaching the earth, by air and water temperature, humidity, vapor pressure, wind movement, altitude and water quality. Transpiration is the second process contributing to the upward movement of water and represents moisture extracted from the ground and released to the atmosphere by the life processes of plant organisms. Precipitation in the form of rain or snow, is the downward component of the cycle from the atmosphere to the earth's surface and represents the conversion of water from the vapor phase to the liquid or solid phase.

Surface Phase: The hydrologic cycle can be either a simple or complex process, involving two or more of the processes described above. In some cases precipitation may infiltrate the land surface only to be returned to the atomosphere by evaporation or transpiration (frequently combined as the term evapo-transpiration).

We should be aware of the generalized concept of the natural hydrologic cycle. Hydrologists use the following equation to account for the distribution of precipitation:

$$P = ET + I + R$$

where P = precipitation, ET = evapo-transpiration, I = infiltration and R = runoff. During the winter when the ground is frozen and evapo-transpiration is at a minimum, almost all the precipitation which occurs ends up as runoff in the surface streams or storage in the snowpack. During the spring when the snow melts and groundwater storage areas are fully recharged by infiltration, the flow of surface streams is highest and runoff is at its maximum. This is frequently a period of flooding. During the summer when evapo-transpiration is at its maximum, the amount of water flowing in streams declines to its lowest level. At this time, during the months of low stream flow, most of the water in a stream is provided by discharge from

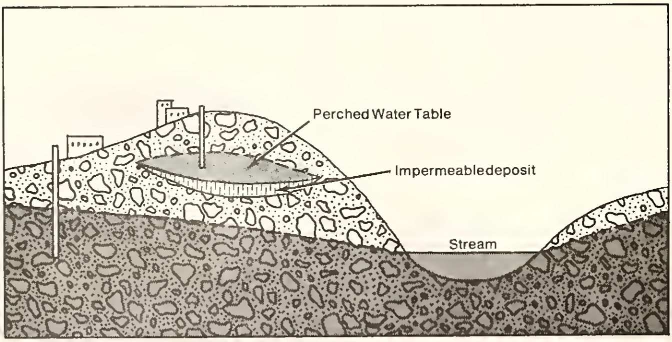


Figure 3-2

Perched Water Table

groundwater storage. In the fall as evapo-transportation becomes less, precipitation is divided between infiltration to groundwater storage and surface runoff. This seasonal cycle recurs year after year.

Sub-surface (groundwater) Phase: That portion of precipitation which is not returned to the atmosphere by either evaporation or transpiration and which does not directly become surface runoff filters down through the soil until it reaches the local water table, a point in the material below the surface of the ground marking the top of the layer of water-saturated soil or rock where every available opening is filled with water. In well-drained areas the surface level of ponds, lakes, and streams indicates the elevation of the local water table. Some infiltrating precipitation may, in places, encounter a subsurface layer of water-resistant rock or soil which prevents the water from reaching the water table, thereby creating a local "perched" water table (Figure 3-2). The standing height of water in an unpumped well is also a good indication of the elevation of the local water table.

Some water infiltrating to the saturated zone travels only a short distance before discharging into a surface stream or pond. On the other hand, some infiltrated water travels through the ground for great distances over a long period of time before reaching a point of discharge. All precipitation infiltrating the ground to the saturated zone continues to move vertically and laterally at a relatively slow rate toward places of groundwater discharge operating under the influence of the earth's gravitational field. Groundwater is the term applied to this slowly moving water beneath the land surface in the zone of saturation.

Groundwater Zones: Figure 3-3 illustrates a groundwater regime typical of most of New England and, in fact, of most of the land masses of the earth. As is shown, a single zone of aeration overlies a single zone of saturation. Water is referred to as groundwater when it reaches the zone of saturation. In the zone of aeration, these pores are filled partially by water and partially by air. The demarcation between these two zones is the water table, or "phreatic" surface, where water is at atmospheric pressure.

Let us observe the progress of a drop of water infiltrating from the land surface to the groundwater zone. The first area encountered is the soil water zone, or zone of soil moisture. Extending from the surface to the depth of major roots, the soil water zone is characterized by water held by molecular attraction. Plants are able to make use of water held in thin films on the soil particles by capillary forces. The limits of water availability to plants are marked by the "wilting point" (lower limit) and "field capacity" (upper limit). Field capacity represents the amount of water remaining after gravity drainage. Thus, our drop of water has been subject to the forces of gravity, adhesion and cohesion (surface tension). The water in this drop could stay in this zone as "hygroscopic" water, bound to soil particles by adhesive forces and not available to plants, or it could also be taken by osmosis into a plant root and eventually be transpired back into the atmosphere. Below the soil water zone is an intermediate zone which can vary in thickness from zero to several tens of feet, depending on the depth to the water table. In this zone water not captured earlier by the forces of adhesion, cohesion and osmosis is free to percolate downward in response to the pull of

gravity. The same forces again play against the drop of water, and adhesion to soil particles must be satisfied before continued downward movement can take place. Here, stationary water, the equivalent of field capacity, is called "pellicular" water.

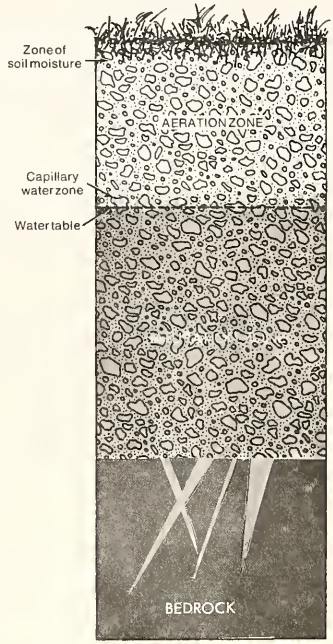


Figure 3-3

Groundwater Zones

The water continuing down is gravational water; it will eventually reach the water table and finally become groundwater. (Actually the area just above the water table is also saturated. This "capillary fringe" differs, however, by having water at less than atmospheric pressure.) Movement in the saturated zone is primarily due to gravity. It is to this zone that we try to sink all our wells. The forces in effect in the zone of aeration are still present here and become evident when one tries to drain the zone of saturation by pumping a well. Some water will remain in the pores against the force of gravity, held by surface tension and adhesion. The volume of water held divided by the volume of soil holding it is called "specific retention;" that volume of water released divided by the volume of soil is called "specific yield." The quantities of each will vary with the physical make-up of the soil pores.

Figure 3-4 illustrates on a different scale the regional relationships within a groundwater basin. An "aquifer" is a geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs. A "recharge area" is an area in which water is absorbed that eventually reaches the zone of saturation. A "discharge area" is an area in which sub-surface water, including both groundwater and water in the unsaturated zone, is discharged to the land surface, to surface water, or to the atmosphere. In general, recharge areas are points of higher elevation on the landscape, and discharge areas have a lower relative elevation.

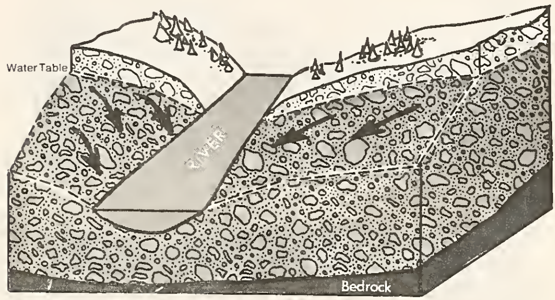


Figure 3-4

Regional Groundwater Flow

Consolidated and Unconsolidated Deposits: In most situations in Massachusetts, groundwater may be found either in the pore spaces between grains of unconsolidated deposits or in the fractures and joints of consolidated deposits. There is one place where it is *not* commonly found: that is in subterranean rivers flowing beneath the surface of the land, as some superstitions would have us believe. The closest resemblance to an underground river we have in Massachusetts is to be found in the dissolved cavities and passageways in some of the limestone formations in the extreme western part of the state. There over the millennia water has, in fact, carved out solution channels in the bedrock through which water can flow.

Except for the Triassic sedimentary rocks of the Connecticut Valley lowlands, the bedrock of Massachusetts consists primarily of igneous rocks or metamorphic sediments with little water-holding capacity; wells drilled in most bedrock areas, therefore, yield enough water for domestic supplies but not enough for municipal purposes in most cases. Overlying the bedrock, however, in some places there are unconsolidated glacial deposits with much greater water-holding capacity; most municipal wells tap these unconsolidated glacial deposits because they are capable of storing large quantities of water. The amount of groundwater available from an aquifer, therefore, depends in part on the physical properties of the rocks and soils in a particular location and the volume of unconsolidated deposits.

Interrelationship of Surface and Subsurface Waters: Although our interest is in that portion of the cycle occuring under the surface of the land, it is important to realize the continuity of the hydrologic cycle. All water, no matter where you may find it, is a link in the cycle. It can and will eventually become transported to another part of the cycle. Thus, it is easy to see that within any one drainage basin all the water is related; one should not, therefore, treat groundwater and surface water as two separate entities. An understanding of this point will make this report worthwhile.

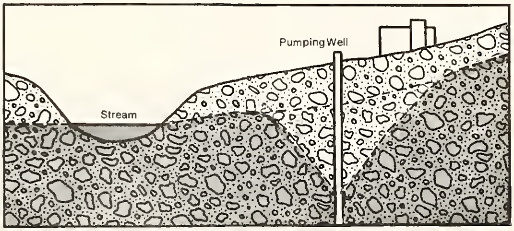


Figure 3-5

Discharae of Groundwater to Surface Water

If the hydraulic connection at the contact between a surface body of water and its adjacent slopes permits the free passage of water from one to the other, it is possible for groundwater to discharge into the surface water during that portion of the year when the water table is above the level of the lake or stream (See Figure 3-5), and for discharge to take place from surface water to groundwater when the water table is below the level of the lake (See Figure 3-6).

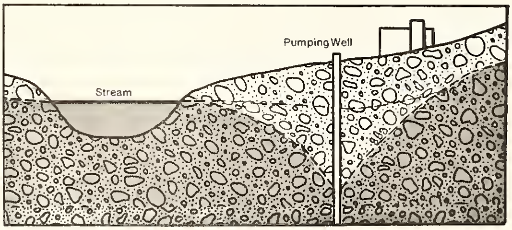


Figure 3-6

Induced Infiltration From Surface Water to Groundwater

Given the free flow of water between groundwater and surface water, the direction of flow will simply be determined by the height of the water table relative to the surface level of the pond or stream. Infiltration from a surface stream is sometimes induced when large quantities of water are withdrawn from the groundwater supply by a

pumping well. This withdrawal of groundwater causes a drop in the local water table within the radius of influence of the well (Figure 3-7). thereby stimulating the flow of water from the stream toward the artificially lowered water table. Thus, it is natural, given the right conditions, for groundwater to become surface water and also for surface water to become groundwater as part of the hydrologic cycle.

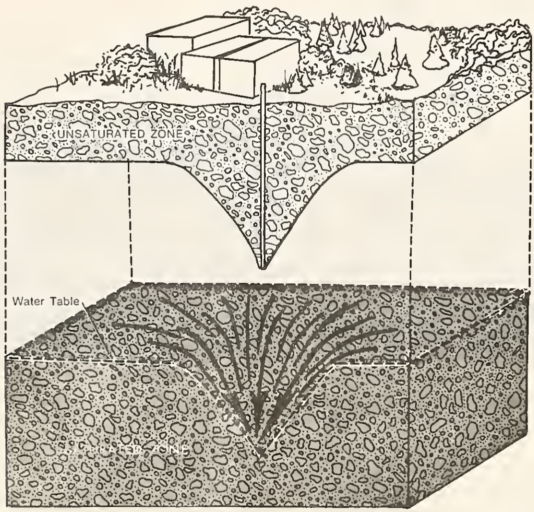


Figure 3-7
Cone of Depression

When a surface stream flows through an area where the local water table is lower than the stream bed, water from the stream may infiltrate the ground and become groundwater. such circulation sometimes takes place when a stream, which has been flowing through an area of relatively impervious material, reaches an area where the material is more permeable. In Massachusetts this is the case with several streams on the island of Martha's Vineyard, where surface streams flowing across relatively impervious till simply cease flowing as surface streams shortly after encountering an area of glacial outwash materials consisting of permeable sand and gravel.

Water Levels and Their Significance: In New England the water table, or surface level of the saturated zone of groundwater, tends to be a subdued reflection of the surface topography. This tendency is in part attributable to the even distribution of precipitation over a recharge area, the even distribution of precipitation throughout the year, and the existence of complex groundwater flow patterns which impede the flattening of the water surface. The surface of an aquifer can be approximated by drawing maps based on static water levels in observation wells.

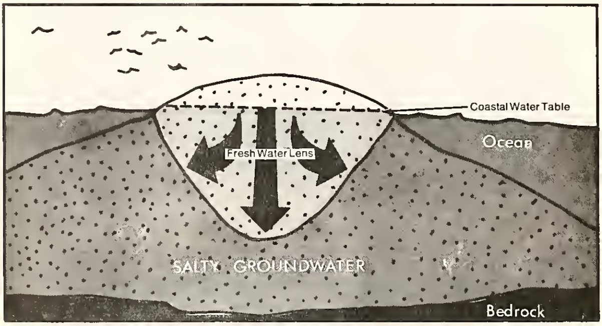


Figure 3-8

Fresh Water - Salt Water Interface

A factor of primary importance to a coastal hydrologic region is the presence of salt water in the adjacent waters and in the unconsolidated deposits adjacent to the coastline. Fresh water, originating as precipitation in the form of rain or snow, infiltrates the unconsolidated deposits of the Cape and reaches the local water table. Because sea water is, on the average, 1/35th to 1/40th more dense than fresh water, the fresh water floats like the hull of a ship on the denser salt water lying beneath it and surrounding it (Figure 3-8). There is always a fragile dynamic balance between the height of the fresh water table above sea level and the depth to the salt water body below sea level, with each foot of elevation above sea level corresponding to a depth of 35 to 40 feet to the base of the fresh water below sea level as a general rule. As the fresh water table fluctuates by a foot or so, the salt water table correspondingly fluctuates by 35 to 40 feet vertically. Lowering the groundwater table on the Cape and Islands causes a change in the position of the saltwater-freshwater interface. In a coastal environment as the water table is lowered due to extensive pumping or other reasons, saltwater will replace fresh water in the ground. Thus, groundwater withdrawal in these coastal regions will deplete the fresh groundwater supply, and overpumping can result in such extensive replacement as to contaminate all of the fresh groundwater resource.

Up to this point all groundwater aquifers discussed have been unconfined aquifers, marked by the presence of a water table at atmospheric pressure.

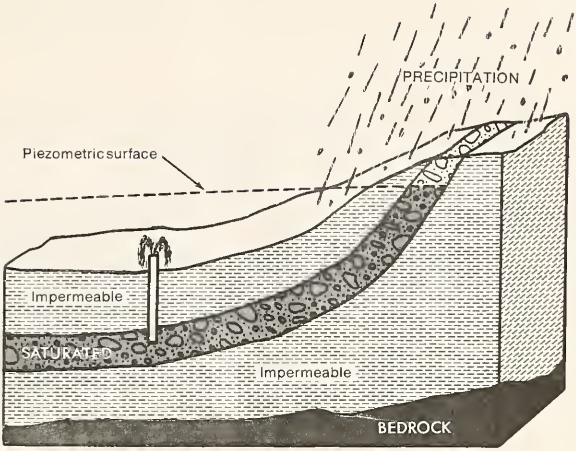


Figure 3-9

Artesian Aquifier

Artesian Aquifers: An artesian (confined) aquifer (Figure 3-9) is a water-bearing stratus of rock or unconsolidated deposits confined by overlying impermeable or semi-permeable materials, such as organic materials, silt or clay. A confined aquifer is characterized by water at a pressure greater than atmospheric, which causes the static water level in a well tapping this type of aquifer to rise above the level of the water yielding layer. If the pressure is sufficient, the well may flow freely at the surface without any pumping.

Water enters the aquifer at a recharge area and becomes confined by the impervious nature of the overlying materials in its flow toward a point of discharge. Unlike the upper surface of an unconfined aquifer, the upper surface of the saturated zone of a confined aquifer remains fixed; changes in water levels in this type of aquifer represent primarily a change in pressure rather than a change in volume as with unconfined aquifers. The water level corresponds to a pressure level called the potentiometric or piezometric surface. The piezometric surface of a confined aquifer can be mapped from water levels in observation wells, much the same as an unconfined aquifer can.

Fluctuations in Water Table Elevations: The elevation of a water table fluctuates according to the relationship between recharge and discharge.

Seasonal fluctuations are normal. In the spring when recharge is greater than discharge the water table elevation rises. In late summer when discharge is greater than recharge the elevation is lower. The topographic situation of a well is an important factor determining groundwater levels and their range of fluctuation, with

greater amplitude of fluctuation occurring in wells situated on hilltops than in wells located in valleys. In Seeley Brook basin, New York, the seasonal water-level fluctuation for a hilltop well on unconfined rock amounted to about 24 feet; during the same period, a valley well in unconfined rock displayed a fluctuation of only about 4 feet (Frimpter, 1972, p. 17).

There is a long-term correlation between precipitation and water table elevations, with higher elevations occurring during periods of average or above average precipitation, and declining elevations resulting from years of drought.

Discharge of water from an aquifer due to artifical extraction by a pumping well also causes a drop in the local water table or piezometric surface near the well. The extent of drop in the water table is directly proportional to the amount of water being pumped from the well and inversely proportional to the distance from the well. This relationship causes the depressed water table near a discharging well to assume a geometric cone-shape, called a cone of depression (Figure 3-7).

If water from an unconfined aquifer is withdrawn at a rate such that discharge is greater than annual recharge, there will be a decline in the regional water table. The High Plains region of Texas provides a dramatic example of this point.[1] Most of the usable groundwater in the High Plains is found in a sandy deposit, in many places 200 to 300 feet thick, lying at or near the surface throughout most of the region. Although groundwater has been used for irrigation purposes since 1911, there were only about 300 wells in operation before 1935. The number of irrigation wells increased rapidly to 1700 in 1939, 3500 in 1944 and 44,000 in 1960. The acreage irrigated rose from an estimated 40,000 in 1935, to more than 4,000,000 in 1960. Almost all of the water used has been taken from groundwater storage in the aquifer, with a resulting decline of 10 to 100 feet in water table elevations throughout the area. Figure 3-10 depicts the water declines that have occurred between 1938 and 1962.

If water from an artesian aquifer is withdrawn at a rate such that annual discharge is greater than annual recharge, there will be a general decline in the regional piezometric surface. For example, at the time the first deep well in Chicago was drilled in 1864, the piezometric surface was about 57 feet above the land surface. By 1890, hundreds of wells had been drilled in the Chicago area; the wells were producing 10 million gallons a day and water levels had declined to the land surface. By 1915, when 45 million gallons a day were being withdrawn from the underlying aquifer, the water level was 150 feet or more below the land surface. By 1958, water levels in Chicago had been lowered an additional 350-400 feet and the offtake had risen to some 75 million gallons a day. (Cited in Kazmann, 1972, p. 17)

Water mining may be defined as the process of decreasing the amount of water stored in an aquifer by discharging in excess of recharge. In coastal areas, where the fresh water lens is in hydraulic contact with a salt water lens, the mining of water can result in salt water intrusion and contamination of the aquifer. This situaation has occurred in Los Angeles, California and is feared by many of the inhabitants of Cape Cod. There is a danger in equating groundwater availability and the pumping capacity of a well. Although from an engineering point of view it is feasible to produce 1 mgd from a well

1. Cited in Kazmann, Raphael G., Modern Hydrology, 1972, 2nd Ed., p. 211-5.

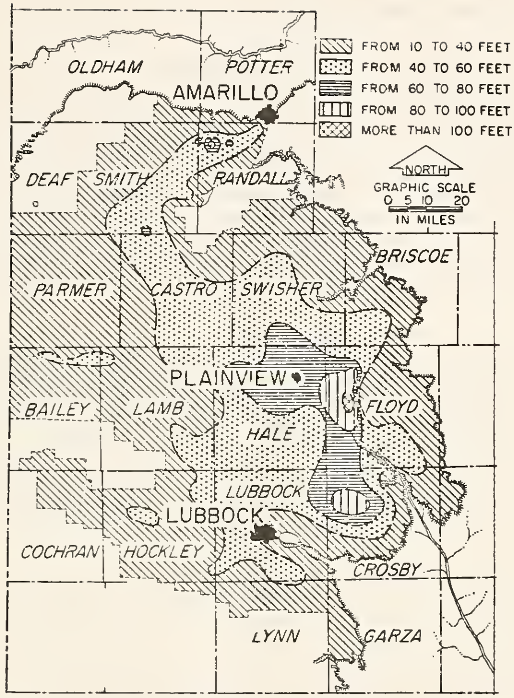


Fig. 5.22. Water-level declines in the High Planes area of Texas. 1938–1962, that resulted from the removal of approximately 50 million acre-ft of water from the aquifer. (Based on data from High Plains Underground Water Conservation District Number 1, Lubbock, Texas.)

Figure 3-10
(Kazmann, Raphael G., 1972, p 214)

located in highly permeable sand and gravel deposits, it is essential to take into account the hydrologic consequences of pumping at this rate for an extended period of time. Two questions become important: (1) Is there a threat of water quality degradation, particularly salt-water intrusion, if this pumping rate is maintained? (2) Is the quantity of fresh water being removed in excess of the natural rate of recharge, so that the total available supply is constantly diminishing and the water is, in effect, being mined from the aquifers?

The Hydrologic Budget: Less familiar than the hydrologic cycle is the hydrologic budget, which quantifies the annual flow of water through the system described above.

Water accounting, like financial accounting, makes use of debit and credit entries, but the units of measurement are inches of precipitation instead of dollars. The credit (income) item consists of annual precipitation in the form of rain or snow, averaging 42-44 inches in Massachusetts. The debit (expense) items consist of approximately 20-22 inches returned to the atmosphere by evaporation and transpiration, and a remainder of 22 inches which contributes to the flow of rivers, replenishes ground storage, and a small portion which flows directly as ground water seepage to the ocean.[2] In addition to the natural variables entered as debit items, man's activities should be placed in this category. The withdrawal of water for industrial processes, cooling purposes and public water supplies greatly affect the hydrologic budget.

Just as financial budgets are characterized by net annual surpluses and deficits, so also are water budgets characterized by surpluses and deficits which can be calculated and which influence water management policies. In arid and semi-arid regions where annual precipitation is insufficient to meet all the demands for water, a net annual deficit occurs each year. In humid regions annual precipitation generally exceeds the demand for water, resulting in a net annual budgetary surplus. Fortunately, New England falls into the latter category, an important point to remember when comparing the water-related problems of New England with those of other regions.

The quantity of water stored in the ground as groundwater in a given area may be compared to a savings account or capital account, if the financial analogy is continued. During the months when recharge is insufficient to meet the demand for water, the deficit is covered by withdrawals from storage; during the months when recharge is greater than the demand for water, the excess is deposited in storage. Changes in water levels in wells are measures of changes in storage of water in an underground reservoir. Although a declining water table may be tolerated for an extended period of time, it cannot be tolerated indefinitely without eventual exhaustion of supply.

Although the hydrologic budget has proven to be an effective concept when comparing one geographical region with another, it has its limitations. For example, it is less useful in situations requiring specific answers to questions about the amount of groundwater which can prudently be withdrawn without affecting either the quantity or quality of water available in the future. When formulating policies for the management of a particular groundwater supply or watershed area, we favor basing decisions primarily on informed estimates of potential recharge from all possible sources, assuming conditions of maximum withdrawal. Instead of formulas involving precipitation, evaporation and transpiration as variables to calculate the potential yield of an aquifer, estimates of groundwater availability can be made from (1) measurements of natural groundwater discharge as determined from the base flow of streams, or (2) estimates of the potential recharge from all possible

2. Knox, C.E. & Nordenson, T.J.

sources, under the recharge conditions that would exist if maximum withdrawal were taking place. Both alternatives make use of the best available hydrologic and geologic data.

Also, it is advisable to keep in mind the fact that the hydrologic budget for a specific region must take into account the influence of man's activities on the natural environment, as well as natural variables. For instance, although the New England region as a whole can be classified as an area with a favorable water surplus, there are parts of New England which have a predictable net annual deficit simply because the withdrawal of water is in excess of the natural supply. This situation occurs primarily in areas with high density of population. The possibility of a local deficit threatens many developing parts of New England unless groundwater recharge areas are protected and the use of water is balanced against the available supply.

Urbanization has produced three problems in connection with streamflow characteristics: (1) faster runoff rates during storms due to loss of recharge areas and a diminished proportion of precipitation being able to infiltrate the ground, (2) increased utilization of floodplains for construction of structures, and (3) siltation of channels which reduces their capacity. Less water in groundwater storage due to (1) above also results in less natural groundwater discharge and lower stream baseflow. The first three factors tend to increase the frequency and intensity of flooding.

Our attention tends to focus on two extremes of runoff: (1) periods of extremely high flow, (flooding), and (2) periods of low flow, when discharge is insufficient to dilute waste discharges or satisfy the competing needs of various users. Through the construction of dams, attempts have been made to regulate the flow of water in surface streams: to reduce flooding by impounding some storm runoff and to augment stream flow during periods of extremely low flow. Management of groundwater reservoirs can also influence streamflow.

With increased population has come increased pollution of surface waters and an increased demand for water. Various alternatives are considered to meet the demand for additional water supplies: (1) water pollution abatement measures: (2) construction of reservoirs on the unpolluted headwaters of streams; (3) diversion of water to densely populated areas by inter-basin transfers; and (4) exploration for sources of groundwater supply.

Water for Wilmington is obtained primarily from two groundwater reservoirs in the headwaters of the river and partially from a third groundwater reservoir downstream. A large part of Reading's water supply comes from a 100-acre well field tapping this third reservoir, where infiltration from the river is a major source of water. Withdrawal from Wilmington's two upstream sources can severely reduce streamflow available to infiltrate the downstream reservoir; however, withdrawal from the 100-acre well field will have no influence on Wilmington's two upstream wells.

In 1970 Wilmington's average daily water consumption was 2.58 mgd and that of Reading was 2.35 mgd, giving a combined total of 4.93 mgd. Increased withdrawal from the present groundwater sources may lead to competition in the future, for by 1990 the towns' combined average daily demand is estimated to be 10.5 mgd. (SENE, Water Supply, Ipswich, Table 3).

It has been calculated that an effective recharge rate (available groundwater) of approximately 10 mgd would be available in Wilmington and Reading during years of average precipitation, and only 5 mgd during years of low precipitation. Peak daily demands of 15 mgd can probably be met by pumping water from storage, provided the average annual withdrawal rate does not exceed the average annual rate of recharge (5-10 mgd). However, during drought years, when recharge is estimated to be in the range of 5 mgd, reservoir storage might be insufficient to provide water to satisfy the estimated 1990 daily peak or even average demands.

A critical shortage could develop in the next few years if there is a period of average or above average precipitation (and recharge) and water resources are fully developed on this basis. Then, if a drought or period of below normal precipitation occurred, demands could not be satisfied by the water resources of the basin. Under these circumstances, Wilmington would have an advantage over Reading because most of its wells are upstream from Reading's 100-acre well field. This situation, of course, presumes that both Reading and Wilmington continue their total dependence on groundwater resources.

2. Water Supply Insufficient to Meet the Needs of Unrestricted Development In an Expanding Community.

a) Stoughton (Kennedy, 1973, p. 3-4)

In Stoughton a critical water shortage developed when increased demand for water exceeded the available supply.

Stoughton is an industrial-residential community with a population of about 25,000 which has shown a 40% growth rate every decade for the past 30 years. The municipal water supply comes from five town wells and there are about 14 million gallons of storage available within the water system. Stoughton has had water shortages for many years as demonstrated by the yearly summer water restrictions.

Since 1955 money has been spent in futile attempts to find new water resources within the town. Money was also spent to connect with Brockton and Canton water supplies so that water could be provided if these towns had excess water available. The town has since applied for admission to the MDC system; the capital outlay program to strengthen the MDC system southerly of Boston to assist the towns of Avon, Braintree, Canton, Holbrook, Randolph and Weymouth as well as Stoughton is now before the Legislature.

The effects of the water shortage were felt in many ways by the town. No building permits were issued for one year; however, the rush to build after the year was over completely made up for the moratorium. Population growth continued and quickened when development resumed. Municipal construction and maintenance suffered because so much of the tax dollar was used in the search for water that expenditures for other capital projects were deferred. Industrial development slowed drastically. There has been no loss of old industries, but new industries requiring large volumes of water have been turned away. Only non-manufacturing and non-processing industries are allowed to locate in the town.

Stoughton is by no means an isolated instance of inadequate water planning. The majority of our communities, large and small, have been guilty of such oversight in varying degrees. Only the recent drought brought the problem into proper focus.

3. Need for Protection of Recharge Areas

a) Pepperell: Jersey St. Well (Caldwell and Holloway)

This case illustrates the importance of protecting recharge areas near municipal wells. The town of Pepperell acquired 18.6 acres of land during the 1970's as the site for a municipal well, taking the land by eminent domain as a purchase price could not be agreed upon. The former owner, the operator of an extensive sand and gravel operation in the vicinity of the well field, is suing the town for more money because he was dissatisfied with the purchase price. He has continued to remove trees and gravel from the land up to 400 feet from the well field although the Town has tried unsuccessfully to obtain a court order which would restrain him from doing so.

The well installed at this field yields about 200 million gallons per year, or slightly more than .5 mgd. The recharge area for the well field consists of a thick gravel deposit lying southeast to southwest of the well. The only recharge comes from precipitation falling on this area which is now covered with trees. The gravel overlying the groundwater aquifer filters and purifies infiltrating water, insulates the water table so the water remains cool, and prevents direct evaporation from the groundwater table. If the gravel in the area south and west of the well is moved, the water table will then be much closer to the land surface, thereby allowing greater loss of water from the water table during summer months. A lowered water table would necessitate a slower pumping rate of the well. If gravel were removed to within six feet of the water table, the temperature of the groundwater would become several degrees warmer in summer.

The forest cover above the gravel promotes percolation of water into the ground by breaking up direct rainfall and allowing rain to enter the ground more slowly and evenly. The tree cover also reduces the depth of frost penetration so that in the spring more snow melt can soak into the ground to recharge the groundwater reservoir. Without a protective covering of trees the cleared ground would freeze to such a depth that nearly all of the snow pack would run off the surface before the ground thawed. Based upon studies in similar areas in New England, the present snow melt recharge is estimated at 300,000 gallons per acre per year; a large part of this recharge would be lost as surface runoff if the ground cover were removed.

The static water level in the Jersey St. well is controlled by the water level in the swamp west of the well. A gravel hogback west of

the swamp prevents drainage toward Reedy Meadow Brook, which is nearly ten feet lower than the swamp water table. Removal of the hogback would cause substantial drainage from the swamp into the brook and the static water table in the well might drop as much as eight feet.

At the request of the Board of Selectmen a hydrologic study and soils analysis were undertaken and observation wells were installed. A 7-day recovery test was conducted to determine the static water table in these wells, from which the direction of flow on the water table could be inferred. A 7-day pumping test was made to determine the drawdown due to pumping and the direction of flow under pumping conditions. It was found that the cone of influence (area from which water is drawn) of the pumping well extends nearly 1,000 from the well in a semi-curcular area extending from northeast of the well clockwise around to southwest of the well. Massachusetts Department of Public Health regulations require protection of a zone within 400 feet of a public groundwater supply. Further distances can be, and have been, required in special circumstances.

b) Pepperell: Bemis St. Well (Caldwell and Hollaway)

A second well field in Pepperell illustrates the need to protect ground-water recharge areas from contamination within the cone of depression of the well.

At the same time that the Board of Selectmen became concerned about the effect of extensive gravel removal near the Jersey St. well, they also became alarmed about the possible effects of additional houses with on-site sewage disposal proposed for Bemis St. near the other town well. Desiring to protect the excellent quality of water from both wells, they declared a moratorium on housing construction in the vicinity of the two wells until a study could be made to scientifically evaluate the effects of building within the watersheds of these wells.

Soils studies were conducted and observation wells were installed in the vicinity of the well. Again, 7-day recovery and 7-day pumping tests were conducted at the well site. Although the tests were interrupted when a beaver dam broke and created an unexpected flow of water, preliminary findings served to delineate the recharge area, and it was recommended that no further housing be permitted within the cone of influence of the well to prevent the flow of septic tank effluent toward the well. Further tests will be conducted to determine how much water is induced from Gulf Brook which flows near the Bemis well with a dry channel extending 200 feet upstream and downstream of the well field. The preliminary tests indicate that the cone of influence of the pumping well extends beyond 1,000 feet.

A new zoning by-law, passed by the town of Pepperell at a special town meeting held December 10, 1973, includes special protection for the town well fields: "No use that involved human occupancy, employment or the keeping of animals; or the exterior, uncovered storage of any leachate materials, or any other use which causes the discharge of sewage, wastes, chemical compounds, decayed matter or other similar substances shall be permitted within 1400 feet of any public well field or water supply source. . . ." (NRWA Newsletter, No. 12)

4. Low Streamflow Related to Groundwater Withdrawal

a) Ipswich-North Shore Area (SENE, G-W Mngt; Ipswich,.p. 5-1, 2)

The situation in the Ipswich-North Shore area exemplifies the close relationship between the amount of water flowing in surface streams and the amount of water withdrawn by artifical induced infiltration, and the additional effect on streamflow when the withdrawn water is not returned to the groundwater reservoir.

Streamflow in this basin during much of the late summer and early fall is severely affected by groundwater withdrawal. There is no flow at the U.S. Geological Survey Maple Meadow gaging station in Wilmington (USGS, Water Resources Data, 1969, p. 72) for many days each year (116 days from October 1968 to September 1969), partly because about 1.2 mgd is withdrawn from the aquifer adjacent to the stream (See Table 1). Groundwater and surface water diversions from the Ipswich River basin upstream from the U.S. Geological Survey South Middleton gaging stations are sometimes in excess of the mean monthly streamflow for long periods (3 months in 1969).

Nearly all the water withdrawn from the groundwater reservoir adjacent to the Ipswich River in Reading is discharged outside the Ipswich River drainage basin. Therefore, the flow of the river below this well field is reduced by an amount about equal to the groundwater withdrawal. Groundwater withdrawal in other towns in the basin similarly reduces streamflow (particularly the critical low flows) if the water is exported from the drainage basin. Even if water is recycled within the basin through septic systems or through treatment and outfall to the river, streamflow will have some net loss. Most of the loss is evapotranspiration from septic system leaching fields and from outdoor water use. Evapotranspiration is greatest during the warm summer grow when streamflow is naturally lowest..

The impact of reduced streamflow resulting from groundwater withdrawal during the summer low-flow period is an important consideration in planning additional groundwater development or changing groundwater management policies. As a hypothetical example, consider the following chain reactions: groundwater withdrawal and export from the basin result in reduction of summer flows in the Ipswich River; reduced streamflow increases the salinity of the Ipswich River estuary; and the salinity increase has an undesirable impact on the high-value ecology of the estuary. In addition to increased salinity, low streamflow has an adverse effect upon the use of the river for navigation, and during periods of low flow less water is available to dilute waste water discharging to a stream.

When the water table declines because of withdrawal from wells, water levels of adjacent swamps, pond, or reservoirs may also decline. Thus, overpumping of groundwater may also adversely affect aquatic and paludal ecology, water supply, and recreational and esthetic values.

b) Neponset River Basin (SENE, G-W Mngt, Neponset, p. 3-1)

In the Neponset River Basin low flow in tributary streams is caused by groundwater withdrawal for municipal and industrial purposes.

Under natural conditions, groundwater discharges to streams and ponds; however, this movement can be reversed by lowering the water table adjacent to them by pumpage. Public-supply wells in Massachusetts often cause some infiltration of surface water to replace groundwater. For example, wells in Mine Brook valley,

TABLE 1

IPSWICH RIVER BASIN

1-1013. Maple Meadow Brook at Wilmington, Mass.

LOCATION.--Lat 42°32'15", long 71°09'41", Middlesex County, on right bank 10 ft upstream from culvert on State Highway 38 and 0.9 mile southeast of Wilmington.

DRAINAGE AREA.--3.99 sq mi.

PERIOD OF RECORD.--October 1962 to current year.

GAGE.--Water-stage recorder. Datum of gage is 75.71 ft above mean sea level.

AVERAGE DISCHARGE.--6 years (1963-69), 6.21 cfs (21.14 inches per year), adjusted for diversion.

EXTREMES.--Current year: Maximum discharge, 71 cfs Mar. 26 (gage height, 5.17 ft); no flow for many days during year.
Period of record: Maximum discharge, 119 cfs Mar. 19, 1968 (gage height, 5.63 ft), from rating curve extended above 47 cfs on basis of measurements of flow through culvert at gage heights 5.33 and 5.63 ft; no flow for many days each year.

REMARKS.--Records good. Water diverted above station for municipal supply of Wilmington since January 1964 (see table below). Recording rain gage located at station.

REVISIONS (WATER YEARS).--WRD Mass., N.H., R.I., Vt., 1968: 1964-67 (monthly and yearly runoff and diversions).

DISCHARGE, IN CUBIC FEET PER SECOND WATER YEAR OCTOBER 1968 TO SEPTEMBER 1969

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0	0	1.3	5.8	16	8.1	30	9.6	1.5	0	0	0
2	0	0	1.3	5.0	12	8.1	27	8.6	1.4	0	0	0
3	0	0	1.2	3.5	9.2	9.5	27	7.8	1.2	0	0	0
4	0	0	2.1	2.7	9.8	12	25	6.5	1.1	0	.07	0
5	0	0	16	2.1	6.5	12	25	6.2	.92	0	.52	0
6	0	0	18	1.9	4.2	11	33	5.8	.79	0	1.3	0
7	0	0	13	4.2	3.0	11	31	5.4	.88	0	1.4	0
8	0	0	8.7	11	2.2	9.8	25	5.2	.92	0	1.4	0
9	0	0	5.5	10	2.4	9.2	21	5.8	.85	0	1.4	.16
10	0	0	2.9	6.3	3.0	9.8	18	6.9	.68	0	1.4	.15
11	0	0	1.9	3.7	2.4	10	16	6.9	.57	0	1.3	.05
12	0	.11	1.8	2.7	2.8	10	15	6.5	.47	.13	1.1	0
13	0	.11	1.8	2.3	3.1	11	13	5.8	.29	.34	.63	0
14	0	.04	2.6	2.1	3.2	11	12	5.2	.20	.61	.24	0
15	0	.01	13	1.9	3.0	14	11	4.7	.15	.79	.18	0
16	0	0	18	1.8	2.8	16	9.6	4.1	.11	.75	.14	0
17	0	0	13	1.7	2.9	19	10	3.8	.05	.63	.12	0
18	0	.06	3.5	1.7	2.6	21	10	3.2	.01	.47	.12	0
19	0	.36	7.1	2.8	2.2	24	17	2.9	0	.34	.07	0
20	0	.77	5.5	6.3	2.9	29	26	3.0	0	.22	.02	0
21	0	.87	4.8	5.8	3.2	34	22	3.9	0	.15	0	0
22	0	.87	4.2	4.1	3.0	39	18	4.1	0	.09	0	0
23	0	.75	5.3	3.1	2.7	41	23	3.9	0	.04	0	0
24	0	.70	9.5	8.7	3.3	42	27	3.5	0	0	0	0
25	0	.70	8.4	23	5.5	52	23	3.2	0	0	0	0
26	0	.68	5.3	21	6.6	68	20	3.0	0	0	0	0
27	0	.66	3.0	15	7.3	63	16	2.4	0	0	0	0
28	0	.62	2.6	9.0	7.9	56	15	2.1	0	0	0	0
29	0	.92	5.3	4.8	———	47	12	2.0	0	0	0	0
30	0	1.2	9.2	3.9	———	45	11	1.9	0	0	0	0
31	0	———	6.8	11	———	38	———	1.7	———	0	0	———
TOTAL	0	9.43	208.6	188.9	135.7	790.5	538.6	145.6	12.09	4.61	11.41	0.36
MEAN	0	.31	6.73	6.09	4.85	25.5	19.6	4.70	.40	.15	.37	.012
MAX	0	1.2	18	23	16	68	33	9.6	1.5	.79	1.4	.16
MIN	0	0	1.2	1.7	2.2	8.1	9.6	1.7	0	0	0	0
(†)	1.96	1.83	1.84	1.85	1.67	1.76	1.87	1.85	2.37	1.94	2.06	2.07

CAL YR 1968	TOTAL 2,116.79	MEAN 5.78	MAX 117	MIN 0	MEAN‡ 7.76	CFSM‡ 1.94	IN‡ 26.46
WTR YR 1969	TOTAL 2,095.80	MEAN 5.74	MAX 68	MIN 0	MEAN‡ 7.67	CFSM‡ 1.92	IN‡ 26.08

† Diversion, in cubic feet per second, for municipal supply of Wilmington. Records furnished by town of Wilmington.

‡ Adjusted for diversion.

PEAK DISCHARGE (BASE, 45 CFS)

DATE	TIME	G.HT.	DISCHARGE
3-26	0715	5.17	71

From U.S.G.S., Water Resources Data, 1969, p. 72

extending from Medfield to Walpole, have been pumped at rates sufficient to dry Mine Brook in Walpole during low flow periods.

Walpole's wells induce infiltration from Mine Brook, School Meadow Brook, the Neponset River, and adjacent wetlands. Wells in Westwood and Canton induce groundwater recharge from the Neponset River. Many of Sharon's wells induce infiltration from Beaver Brook and intercept groundwater flow moving to the Brook. Similar relations may exist between Foxborough's wells and the Neponset Reservoir, Norwood's wells and Purgatory Brook, and Stoughton's wells and Pinewood Pond, Muddy Pond and other ponds outside the Neponset River basin.

c) Aberjona River (Hustvedt)

Perhaps one of the most extreme examples of low streamflow attributable to excessive groundwater withdrawals is found in the Aberjona River Basin, a part of the Mystic River watershed.

The Aberjona River receives much of its flow from influent streams as drainage from marshes. Generally it can be stated that streamflow increases as it flows downstream. Flow measurements were made during 1971 and 1972 as part of an overall basin survey program. These flow measurements showed an interesting point.

For many years, Woburn and Winchester have withdrawn groundwater from wells for either recreational or drinking water purposes. There are also numerous industries who withdraw groundwater in significant quantities. The municipal withdrawals in Woburn are discharged to the sewers while Winchester's water is used in a swimming area where any overflow is discharged to the River. The majority of the industrial water withdrawals are used for cooling purposes; the heated water is discharged to the sewer.

In past years large quantities of water (in excess of 10 mgd) have been withdrawn from the aquifer daily with only small portions of the water (probably less than 2 mgd) being returned to the river (or aquifer). Looking at the flow records from past studies, it can be shown that during low flow periods there is a marked decrease in flow in the river as it passes through the area where water is being withdrawn. During extended low flow periods, there is a definite decrease in flow in the river as it flows past the well fields. During the summer months, the flow decreases to almost zero as the demand for well water increases and the amount of water released from the wetlands decreases. In effect, the water that is flowing in the river is withdrawn by way of the groundwater and is not being discharged back to the river. This causes a net loss of water from the aquifer and a decrease in stream flow.

To further support the fact that groundwater pumping severely decreases flow in the river, it can also be shown that the flow in the river increases as would normally be expected where there is no removal of groundwater by pumping. The single fact that there is groundwater withdrawal without any return explains the low unit discharge from the Aberjona River basin.

The mean annual flow of the Aberjona River at Winchester is 1.14 cubic feet per second (0.74 mgd) per square mile, which is about 30 percent lower than other streams in eastern Massachusetts. This difference can be accounted for by a withdrawal of about 7 mgd of groundwater by public and industrial supplies and subsequent disposal out of the basin through the MDC sewer system. (SENE, G-W Mngt, Mystic, p. 4-1) (Warrington, R.V., "Hydraulic Survey of the Aberjona River and Operation of The Aberjona Commission", 1973, cited in Lipman, 1973).

5. Effect of Out-of-basin Transfers

The previous section dealt with the consequences of groundwater withdrawal upon the quantity of water flowing in surface streams; this section deals with the impact on groundwater supplies when surface water is artificially diverted from a basin.

a) Charles River Basin (SENE, G-W Mngt, Charles, p. 3-1, 4)

Groundwater is sometimes erroneously considered as an alternate water source independent of surface sources within a hydrologic basin. Whether the water diverted from a basin comes from a surface reservoir, groundwater reservoir or stream, the quantity of water diverted from the basin is lost from that basin and is unavailable for subsequent use.

The Charles River basin faces a potential water quantity and quality crisis far greater than even its present condition would indicate. The hydrologic system of the Charles River basin is stressed, largely due to the high rate of water use. Through what is probably the oldest canal in the United States, a diversion constructed in 1639, up to one-third of the flow of the Charles River may be diverted to the Neponset River through Mother Brook for industrial use. (Historically, only about 25 percent of the flow has been diverted.) Most of the runoff from 23.6 square miles of the Stony Brook basin is diverted for municipal water supply in Cambridge. In all, approximately 13 mgd (20 cfs) of groundwater pumped from the basin is discharged into the ocean through the MDC sewage system.

If a large proportion of a basin's groundwater supply is pumped out of the basin, the negative effect on groundwater resources as well as streamflow can be pronounced. The trend in the Boston metropolitan area, as in most such areas, has been to extend sewerage service throughout the basin soon after the spread of urbanization.

To visualize the results of past trends, consider the highly unlikely situation wherein Dedham, Needham, Wellesley and part of Natick meet all their projected 1990 water demands with water derived from the basin and that, after use, all this water is sewered out of the basin. The estimated average daily 1990 demands of those towns is about 8.2 cfs (cubic feet per second) greater than in 1970. (SENE, Water Supply, Mystic, Charles and Neponset, Tables 2 and 5). As of 1970, the discharge of the Charles River at Waltham was equal to or less than 8.2 cfs 1.9 percent of the time, or almost 7 days during an average year. Consider the hypothetical situation in which streamflow regulation remains unchanged, water consumption increases as predicted, and the sewage is discharged outside the basin. Under these conditions the flow of the Charles River at Waltham would approach zero for approximately 7 days during an average year. However, because the maximum monthly demand is expected to be 1.2 times greater than the average demand and is expected to occur when streamflow is lowest, the flow of the river will be expected to approach zero for more than 8 days during an average year.

b) Diversion from Connecticut River to Quabbin Reservoir

A survey of surface water diversion in Massachusetts would be incomplete if it did not mention the planned and proposed diversions of additional water from the Connecticut River watershed to meet the projected water demands of the communities in the eastern part of the state.

The diversion of flows from the Connecticut River via The Northfield Mountain Pumped Storage Project to Quabbin Reservoir

has been approved by the Massachusetts Legislature. The concept of skimming flood flows was originally endorsed by Connecticut Water Resources officials on the basis of engineering and environmental studies conducted by the U.S. Army Corps of Engineers pursuant to the Northeast Water Supply Study.

Recent concerns have been expressed by Connecticut officials regarding the potential hydrologic effects of altering the high flow regimen and effects on dependent biota. An interstate monitoring mechanism is currently under study by the two states.

The Water Resources Commission has endorsed the concept of making additional diversions at a later date from the Millers River basin to Quabbin, with appropriate safeguards to protect the groundwater resources of the donor watershed. Beyond these diversions, it is contemplated that the Merrimack River will play a role in augmenting the supply to eastern Massachusetts.

6. Lowering of Pond Levels

a) Bungay Lake (SENE, G-W Mngt, Tenmile River, p. 4-1, 4)

Bungay Lake (100 acres) is an example of a lake which could easily be lowered as the result of groundwater withdrawal by surrounding communities.

Excellent, highly conductive gravel aquifers in the drainage basin of Bungay Lake have led to development of groundwater supplies there by the town of Mansfield. The Town pumps an average of 1 mgd from wells in a gravel aquifer on the east shore of the lake. In addition, wells pumped at about 1 mgd on the west side of the lake by the North Attleborough Fish Hatchery are close to the Bungay Lake drainage divide and induce probably about 10 percent of their yield from the lake. Little of the water pumped by Mansfield is discharged in the basin and recycled to the basin; most is discharged downstream to the Bungay River. Privately owned domestic wells in the lake drainage area withdraw small quantities of water, of which 80 to 90 percent is locally recycled, the remainder being lost through evapotranspiration.

Local residents, organized as Bungay Lake Associates, believe that a proposal by the town of Mansfield to withdraw an additional 1 mgd from a well north of the lake, yet within its drainage area, will lower the lake level. Foxborough has also considered withdrawing groundwater from this area. For a shallow (7 ft. deep) lake such as Bungay, lowering the water level even a foot would expose large areas of lake bottom and might have a great impact on lake ecology, recreational value and esthetic appearance. Lake levels declined more than 3 feet below the spillway during the middle sixties' drought. During that period, pumpage by Mansfield contributed to the low lake level. Because no overflow surplus occurs at the Bungay Lake dam or the fish hatchery bypass pipeline in the summer growing months, any water exported from the basin must be derived from the lake and groundwater storage.

Pumping wells at a rate of 1 mgd over a period of 90 days during the growing season would remove 7.5 million cubic feet of water from the ground and 4.5 million cubic feet from the lake. The withdrawal of this 12 million cubic feet from storage would cause an average decline of the water table and lake level of about 1 foot.

The decision for management of water and related resources in the Bungay Lake watershed requires determination of acceptable environmental costs for additional water supply. Reasonable determination is difficult because development that may benefit one

group may penalize another. Four towns lie in the drainage basin: Mansfield, which withdraws 1 mgd of groundwater and wants to double its withdrawal; North Attleborough, in which most of the lake and valuable lake property lies; Foxborough, which has located a possible well site in the basin; and Plainville.

The problem is one of fair apportionment of water rights between diverse interests in this watershed.

The Department of Public Health has taken cognizance of further withdrawals from Bungay Lake watershed. Recent pumping tests for a gravel packed well have been approved for Mansfield.

The Department will hold a hearing in the near future to determine whether or not to allow Foxboro to acquire land for the construction of two wells easterly and westerly of Witches Pond located northerly of Bungay Lake and southerly of Lake Mirimashi, a compensating reservoir for the Wading River and Attleborough. The Department of Public Health geologist has indicated that there will probably be no effect on Bungay Lake. However, the Department will determine this after the hearing.

b) Lake Quinsigamond (SENE, G-W Mngt, Blackstone, p. 2-16, 17, 4-1)

In this example, the level of the lake has already been affected by the amount of water withdrawn from adjacent groundwater reservoirs; further groundwater development to satisfy projected future needs could lower the level of this lake even more.

Coarse-grained sand and gravel adjacent to Lake Quinsigamond form a combination storage-infiltration groundwater reservoir. Shrewsbury's public supply is obtained from six wells tapping the reservoir on the east shore of the lake. The wells have a total pumping capacity of 4.2 mgd and, in 1970, produced an average of 1.97 mgd.

The groundwater reservoir is also tapped on the west shore of the lake by wells owned by the city of Worcester. The Worcester wells have a total pumping capacity of 5.7 mgd, so that total developed pumping capacity from the groundwater reservoir is 9.9 mgd. Alonzo B. Reed, Inc., estimates that groundwater resources in the entire Quinsigamond River valley are capable of sustaining a yield of only 6 mgd. On the basis of this estimate, the 1990 SENE demand of 8.2 mgd projected for Shrewsbury cannot be met entirely with groundwater from the Quinsigamond River valley.

Much of the water withdrawn from the Shrewsbury and Worcester wells consists of induced infiltration from the lake. During summer and fall months, when groundwater withdrawals exceed surface inflow, lake storage is depleted, causing the lake level to decline. Because the lake is also used for recreation, Alonzo B. Reed, Inc. recommended that groundwater resources only be partly developed to prevent pronounced seasonal lowering of the lake due to increased groundwater withdrawals.

c) Kingbury Pond (Williams, 1967)

The level of Kingbury Pond dropped drastically during the mid-sixties for two reasons: (1) withdrawal of groundwater needed by the town of Franklin, and (2) the prolonged drought during the sixties.

Kingbury Pond, located in the northwestern part of the town of Norfolk near its boundary with the town of Franklin, dropped to a level about 13 feet below normal high water and 8.4 feet below its previous recorded low level (1949). The area of the pond shrank from 26 acres to about 9 acres. The entire northwestern part of the pond is

almost dry, leaving many residents without shore frontage; the soft, saturated mud in this area is a hazard to small children and pets. Those fronting on the remainder of the lake have been without use of their docks, boathouses and other shore facilities. Almost all residents using individual water supplies have been faced with decreasing yield and drying up of wells caused by a decline in the groundwater levels adjacent to the lake; most existing wells have been deepened and replaced with new wells, and some residents are without water for domestic use. During the low water conditions property values are reported to have declined, and the market for homes around the pond was said to be non-existent. The subsequent return to normal rainfall has occasioned some increase in the water level.

Many of the residents affected believe that pumping from a gravel-packed well owned by the town of Franklin has been responsible for the continuation of the low level of the pond since the drought. Pumping from this well, located in Franklin 1,300 feet southeast of the pond, began July 3, 1964, at a time when the drought had caused a general drop in lake levels and groundwater tables in this part of southeastern Massachusetts. In 1964 and 1965 the well produced about 11 million gallons per months. In the first eleven months of 1966, average monthly production was increased to nearly 18 million gallons per month, and production during the summer months had nearly doubled over that of 1964 and 1965.

In 1966 the well supplied 43 percent of the water distributed in the Franklin municipal water system. Even with this well, the town of Franklin still lacked an adequate supply of water to meet present and future demands, and has since constructed in 1967 an additional well along the Norfolk line 2,300 feet south-southeast of the existing well.

Because Kingbury Pond is officially a great pond (10 acres or larger) the U.S. Geological Survey was asked to make an investigation of the cause of the decline in the level of the pond. The study was based on geologic observation, well records, a survey of groundwater and pond levels, a test drilling program, well production records furnished by the Town of Franklin, and information provided by Whitman and Howard, Inc., consulting engineers to the Town of Franklin.

The U.S. Geological Survey report concluded that increased pumping of the Franklin well had caused expansion of the cone of depression of the well, resulting in reversal of the natural slope of the water table between Kingsbury Pond and the well, and cutting off the pond from its former groundwater recharge source. Net water loss from the pond was estimated to be 25,000 gallons per day, which moves as groundwater toward the Franklin well. It was felt that, unless the original position of the water table could be restored, there would be little chance that the pond could be restored to and maintained at its former level.

A court case against the Town of Franklin was dismissed in Superior Court and was not appealed. The Franklin well had previously been approved by the Department of Public Health.

7. Cape Cod

Many of the problems discussed earlier also apply to Cape Cod. It seems more appropriate to discuss the Cape's problems on a regional rather than a topical basis because of the fact that it has one unique problem not common to other regions: surrounded as it is by salt-water, it has a plentiful supply of water but only a limited supply which is suitable for human consumption. Statements relative to Cape Cod are equally applicable to Martha's Vineyard, Nantucket and a narrow strip of land on the mainland which borders the coast.

The Association for the Preservation of Cape Cod, with the assistance of such scientists as Dr. Arthur N. Strahler and Dr. Zane Spiegel, has produced a number of publications warning of the dangers of overdevelopment of the groundwater resources of Cape Cod. (Strahler, 1972) (Spiegel and Strahler, 1972).

> "The 'water problem' which Cape Cod towns should be facing now is that unplanned and uncontrolled development is taking place at an extremely rapid rate—and in the absence of any plans which would insure an adequate fresh water supply for the future, or which would prevent the serious forms of environmental degradation that inevitably accompany unwise water use practices. The tragedy of this course is that by the time the impact of present development and water use on the Cape's water resources and on the total environment becomes obvious, severe and possibly irreversible damage will have already occurred. The cost of restoring the resource will be prohibitive, if it is possible."

For the present, supply appears to equal demand. In 1970 the Department of Public Health engineers determined that the average consumption on Cape Cod was 11.541 mgd. The safe yield was determined to be 45.4 million gallons per day of the then sources. In fact taking the highest day consumption of all towns and assuming that it occurred on the same day the total consumption would have been 32.7 mgd or well below the safe yield. Many new sources have been added since 1970.

The nature of the Cape's water supply and the effect that a contaminated or overused groundwater aquifer would have on the region's economy makes the Cape a unique water region of Massachusetts. Spiegel and Strahler (1972, p. 4) list four factors which contribute to the uniqueness and vulnerability of Cape Cod's water resource:

1. Groundwater replenished by local precipitation is an important source of water supply on Cape Cod; it is impossible to develop additional supplies in this region by impounding rivers.

2. The geographic isolation of the Cape makes the importation of water from outside sources a prohibitively expensive alternative. Desalination of sea water is still a costly alternative.

3. The extreme permeability of the sandy deposits making up the Cape's land mass facilitates the flow of water through the sole fresh-water aquifer, making it impossible to isolate or protect a given well from the consequences of withdrawal or contamination in other parts of the aquifer.

4. Salt water intrusion seriously threatens some public and private water supplies on Cape Cod.

They also point out the hydrologic and economic consequences of permitting consumptive use to exceed the natural rate of groundwater recharge by precipitation:

1. Lowering pond levels, creating conditions favoring pond eutrophication and destroying shallow ponds, with severe economic and esthetic loss to abutting property owners.

2. Lowering the water table and reducing surface stream flows, adversely affecting the cranberry industry.

3. Reducing the quantity of natural fresh water discharged to coastal estuaries, thereby increasing the salinity of these areas and degrading or destroying finfishing and shell-fishing, upon which commercial and sport industries depend.

4. Causing salt-water intrusion into coastal wells, thus lowering property values where town water is not available.

Charles F. Kennedy, Director and Chief Engineer of the Massachusetts Division of Water Resources, agrees with the APCC and the Cape Cod Regional Planning and Economic Development Commission that a comprehensive, detailed hydrogeologic study of the Cape is necessary to define its groundwater resources to that future development will be based on a program of water availability.

"Cape Cod is predominantly dependent on tourism for support, and development in this direction has been encouraged at all costs. For the most part, the demands on water supply have surpassed, or will soon surpass, the amount of available water. The first public water supply system was installed in Provincetown in 1893. The town grew as a tourist attraction and eventually found itself not only with a water shortage, but also with the problem of salt water intrusion into the public supply wells. Further development will be difficult until other supplies are found.

"The specter of salt water intrusion haunts Cape Cod communities much as it does Long Island, New York. Many developed areas on Long Island began providing municipal sewage disposal and the ground water recharge became dependent solely on rainfall. This effectively decreased the elevation of the groundwater table as pumping continued and, thus, increased the possibility of salt water intrusion." (Kennedy, 1973)

Because the Cape is almost totally dependent on its groundwater resources, contamination of the groundwater aquifer by salt water intrusion due to overuse of a finite natural resource would necessitate costly alternatives: importation of water from geographically remote regions or desalination of sea water. Excessive use of groundwater would result in lower pond levels as the water table drops, increased salinity in coastal estuaries, and reduced streamflow.

Because the Cape is a summer resort area, its population and water demand peak during the season when natural recharge is at its minimum (See Figure 1). Moreover, the use of public water supplies on Cape Cod has nearly doubled between 1960 and 1970, reflecting an increase in the number of year-round residents as well as a larger number of summer visitors (See Table 2).

Recognizing the potential severity of the water supply problem on Cape Cod, the Water Resources Commission has funded a study by the U.S. Geological Survey to determine the groundwater resources of the Cape. This study is designed to provide information which the Cape's fifteen communities can use to formulate a water management program compatible with plans for future development.

TABLE 2

PUBLIC WATER USE ON CAPE COD DOUBLES IN 10 YEARS

	1960 (in millions gallons)	1970 (in millions gallons)
Barnstable	750	1,117
Bourne	241	770
Brewster	0	0
Chatham	84	150
Dennis	172	412
Eastham	0	0
Falmouth	602	748
Harwich	142	281
Mashpee	0	29
Orleans	0	142
Provincetown	230	325
Sandwich	33	84
Truro	0	0
Wellfleet	0	0
Yarmouth	230	606
	2,484	4,664

Note: Zeros indicate no public water supply.
From SENE, G.W. Mngt., Cape Cod. Table 2-B, p. 2-12

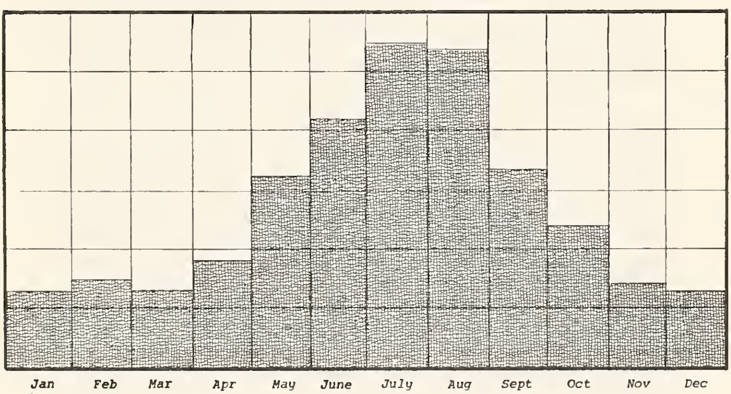


FIGURE 1
1970 monthly water use by Provincetown
(Shows seasonal variations of water demand on Cape Cod.)

From SENE, G.W. Mngt., Cape Cod, Fig. 2-10, p. 2-14

a) Provincetown (Delaney and Cotton, 1972)

A lack of potable water in Provincetown began many years ago, causing the town to establish new public-supply wells in the neighboring town of North Truro. Most of the withdrawal of groundwater from North Truro today is attributable to pumpage from the Provincetown well fields.

Provincetown first developed the Old North Truro well field (a series of twenty 2 1/2 inch tubular wells) in North Truro in 1908. This was a major source of public supply for Provincetown until rising chloride concentrations began to cause concern. In the hope that the chloride problem could be avoided, 47 additional tubular wells were installed in a line inland from the original wells from 1914 to 1928. Chloride concentrations, however, continued to increase, resulting in the establishment of a second well field in North Truro along South Hollow Road in 1954.

The South Hollow well field consists of eight gravel-packed wells spaced at 150-foot intervals along a trench constructed beside South Hollow Road. Both the linear distribution of the wells and the controlled pumping rate of approximately 100 gpm (gallons per minute) from each well restrict drawdown and reduce the potential for salt-water intrusion.

Early in 1959 three 8-inch diameter gravel-packed wells were installed at the Old North Truro well field to augment the old tubular well system; these were designed to lower the general water table less than the line of tubular wells had. Since the tubular wells eventually were abandoned, the gravel-packed wells currently furnish the entire production of the Old North Truro well field.

Rising chloride concentration in water from the new gravel-packed wells at the Old North Truro well field prompted frequent testing for chloride from July through November 1959; chloride concentration ranged from 160 to 260 mg/l (milligrams per liter). After installation of the three 8 inch wells, in the 1960's, chloride concentration in this well field averaged nearly 100 mg/l. The chloride concentration at the South Hollow well field was only slightly higher during the 1960's than its initial concentration of 16-32 mg/l.

During 1970 water from both fields increased in chloride concentration, to as much as 180 mg/l at the Old North Truro station and 50 mg/l at the South Hollow station. Again, concern over rising chloride concentrations and increased water use (22 percent more in 1970 than in 1967) has prompted Provincetown to submit plans for additional groundwater withdrawal in North Truro. It should be noted that average chlorides at the South Hollow well field in 1973 were 47 ppm and 65 ppm at the Old North Truro station, lower than some inland sources. (DPH, written communication, 1974).

The U.S. Geological Survey was asked by the National Park Service to evaulate the effects of groundwater withdrawal from two proposed Provincetown wells within the North Truro area of the Cape Cod National Seashore. The report submitted by the Survey suggested the 1 mgd withdrawal rate proposed for each single high-capacity well would impose a stress on the groundwater reservoir and increase the potential of vertical salt-water intrusion; if intrusion occurred groundwater quality would deteriorate. The lower water table created by the proposed withdrawal at one of the sites would also affect the nearby swamp ecosystem by lowering the swamp

water level. The Survey suggested that the installation of a properly managed field of widely spaced low-yield wells would have less impact than the installation of single high-yield wells. Further study of the site to determine geo-hydrologic data was recommended.

b) Waste Water Disposal: Two Alternatives (Bauer Eng., Inc., 1972)

Two systems for dealing with the problem of waste water disposal for Cape Cod as a whole and Falmouth in particular were under consideration. In one, the waste water was to be treated and disposed of through ocean outfall. In the other, recycling and reclamation of water was to be developed in a land treatment system.

On much of the Cape private septic systems both treat and recharge the used water, thereby maintaining an adequate groundwater supply. The high rate of population growth, particularly in coastal locations, makes the installation of municipal sewerage systems inevitable. A very significant and immediate effect of sewering would be to remove groundwater recharge previously provided by private septic systems. Removal of this recharge could create an immediate lowering of pond levels and a change in the fresh water-salt water interface, which could permit some salt water intrusion.

Both alternatives involve the collection, treatment and disposal of wastewater. In essence, the ocean outfall method of sewage disposal involves the collection and secondary treatment of waste water and the discharge of the treated effluent beneath the surface of the ocean; the removed solids and sludges require further treatment. The land treatment-spray irrigation method involves the collection and secondary treatment of waste water and the use of the aerobic soil zone, or living filter, to provide tertiary treatment to the waste water. Crops grown in the soil zone recycle nutrients and the reclaimed water is acceptable for public water supplies and is available for reuse. Solids removed in treatment are also applied to the land as a soil conditioner and fertilizer.

Evaluation of the two alternative methods of disposal revealed that (1) construction and operation costs were roughly equal (land treatment-spray irrigation cost estimates being slightly lower) and (2) the environmental impact of ocean outfalls was much less favorable because of the adverse effect upon the groundwater table and the potential degradation of the coastal environment. It was decided that a pilot program of land treatment-spray irrigation would be designed and conducted at Otis Air Force Base, to determine, whether, in fact, the land irrigation system is safe and a suitable alternative to ocean disposal.

B. Quality of Groundwater

Careless or thoughtless management of the groundwater resources of Massachusetts may lead to the contamination or loss of a valuable source of public water supply. Historically most of the attention and budgetary support of the legislature has focused upon reduction in the pollution of surface waters, leaving protection of groundwater as a lower priority item.

The following cases illustrate the need for greater protection of groundwater resources, including the early identification of groundwater reservoirs capable of yielding a large volume of water suitable for public water supplies.

1. Contamination by de-icing salt

In January 1973 a special report (Senate Doc. # 1485, 1973) was submitted to the legislature on the subject of rising sodium and chloride levels in public water sources. In response to a recommendation in the report, Chapter 1208 of the acts of 1973 was passed empowering the Massachusetts Department of Public Health to issue regulations governing the storage of salt and other de-icing chemicals and requiring reports on the quantities of such materials applied to highways throughout the state. Cited in the report were examples of groundwater pollution.

a) Notice to 63 Communities (Senate Doc. # 1485, 1973, p. 15-16)

In May 1970, the Commissioner of Public Health wrote to Boards of Health and Water Commissioners of 63 communities that recent samples from their water supplies had contained sodium in excess of 20 milligrams per liter (mg/l). The DPH noted:

"Medical authorities such as the American Heart Association advise the use of water with no more than 20 mg/l of sodium for patients with congestive heart failure, hypertension, renal disease, and cirrhosis as well as for many pregnant women.

"Rising sodium and chloride levels are primarily due to increased use of salt on highways during winter months."

The 63 communities (20% of the Commonwealth's cities and towns having public supplies) included not only many small towns, such as Dudley and West Brookfield, but also two major cities, Cambridge and Lowell. DPH tests in 1971 showed a number of sources containing sodium two to four times greater than 20 mg/l.

b) Auburn: One Well Closed (SENE, G-W Mgnt, Blackstone, p. 2-8,8)

Auburn has had to shut down one of its municipal wells because the chloride content exceeded the maximum permissible limit of 250 ppm.

The Town is served by five water districts, two of which rely on groundwater. The Auburn Water District has five gravel-packed wells, which have a combined pumping capacity of 2.43 mgd: two of the wells are close to Interstate Route 290, and three are off State Route 12 adjacent to the Massachusetts Turnpike (Interstate Route 90). Withdrawals from the wells in 1970 averaged 0.76 mgd. A second district is supplied by a 0.15 mgd well owned by the Pakachoag Water Company. The remaining three districts are supplied by surface water obtained from the city of Worcester.

Water draining from the highways during winter and early spring contains de-icing salt. This salty water recharges the groundwater reservoirs tapped by the Auburn Water District wells and degrades the quality of the well water (Pollack, 1971). Since

1966, water from one well (No. 2) has exceeded the recommended limit of 250 mg/l for chloride in public drinking water. The well, which had been supplying about 15 percent of all water distributed by public-supply systems in the town was taken out of service in 1971 when the concentration of chloride reached 510 mg/l. All the Auburn district wells are within 500 feet of a major highway and, unless the volume of salt-water recharge derived from highway drainage is reduced, the problem of chloride contamination will continue.

c) Weston (SENE, G-W Mgnt, Charles, p. 5-6)

Weston is another town which found it necessary to abandon municipal wells because of increased chloride content.

The concentration of chloride in uncontaminated groundwater in eastern Massachusetts ranges from 5 to 15 mg/l; the Nickerson well field, a 1-mgd supply in Weston, has been abandoned owing to chloride concentration in excess of 250 mg/l. The well is located in a low area between Route 128 and the Massachusetts Turnpike near a toll plaze, and taps an aquifer that receives some of its recharge from highway runoff. A mixture of sodium and calcium chlorides applied to the road pavement for snow and ice removal is carried in solution in this runoff, resulting in increased chloride content of the water from the well.

d) Purgatory Brook drainage basin (SENE, G-W Mgnt, Neponset, p. 4-3)

A salt stockpile in the Purgatory Brook drainage basin on Route 1 near Route 128 in Westwood was the source of sodium chloride in nearby surface and groundwater. The investigation of this site revealed that water in a tributary of Purgatory Brook had a specific conductance (a measure of dissolved solids concentration) of 1.490 micromhos per centimeter at 25°C, and that groundwater near the salt pile had a specific conductance of 7,800 micromhos. In this part of New England, conductivity of natural water is usually in the range of 50 to 100 micromhos. An emergency public supply well adjacent to Purgatory Brook in Norwood and 1 mile downstream from the salt pile showed a seven-fold increase in chloride concentration over a period of 6 years.

e) Goshen: Private Wells Unusable (Senate Doc. # 1485. 1973. p. 21)

In Goshen, a small dairy and lumber town of about 500 people located on Massachusetts Route 9 near the Berkshire Hills. salt contamination has made private wells unusable.

Goshen sits in a geological pocket having little or no exterior drainage. Historical records, as well as tests of water elsewhere in the area. show that the natural level of chloride is about 5 ppm. However, water from wells located next to the highway and serving the center of town is now contaminated by chloride levels ranging from 300 to 2,675 ppm; householders must, therefore, haul their water in from outside this area, typically from wells of relatives. Drinking water for their 90-pupil school is trucked in from Holyoke at a cost of about $1.75 per five-gallon bottle.

After determining the extent and cause of salt contaminationn, State DPW engineers designed a new drainage system for Goshen, which diverts brine running off Route 9 away from the wells and sluices it into a stream leading to the Connecticut River.

2. Contamination by Effluent from Septic Tanks

The Massachusetts Department of Public Health is empowered by Chapter III of the General Laws to issue regulations relative to the disposal of sanitary sewage, including septic tanks and cesspools. The State DPH supervises certain categories such as nursing homes, public buildings and public accommodations, and all systems with flows of over 2,000 gallons per day. Local Boards of Health are responsible for supervising the installation of smaller units.

The State Sanitary Code states that disposal fields and seepage pits for septic tanks and cesspools shall not be constructed in areas where the maximum groundwater elevation is less than 4 feet below the bottom of the field or pit; provided, however, that in instances where the soil consists of porous sand or gravel with a percolation rate of 2 minutes or less per inch, the maximum groundwater elevation may not be less than 2 feet below the bottom of the field or pit. Groundwater determinations are to be made on the basis of the highest annual groundwater (Sec. 7.2, 9.6, 11.8). Systems handling greater than 2,000 gallons per day shall not be installed where the percolation rate is greater than one inch in 20 minutes (Sec. 14, i,e,5). Soil with a percolation rate of over 30 minutes per inch is considered impervious and therefore unsuitable for the subsurface disposal of sewage (Sec. 14, 1,e,6). Minimum leaching areas are determined from the percolation rate, which sets the number of square feet to be allowed per gallon, and the estimated daily sewage flow.

Chapter 848 of the Acts of 1973 provides that no sewage disposal system shall be constructed or maintained within 100 ft. of any known source of water supply or tributary thereto. It further provides that no sewage disposal system shall be constructed within 75 feet for a single dwelling, or 100 feet for a multiple dwelling, of any great pond, stream, brook, tidal water, river, or swamp, without the prior written approval of the Department.

a) Fecal Pollution

The presence of coliform organisms in a water sample may indicate fecal pollution because the coliform organism is an inhabitant of the intestinal tract of warm-blooded animals and is contained in all domestic wastes. Although the coliform organism is non-pathogenic, its presence indicates that at some point the water may have come in contact with sewage. To date, there have been relatively few cases of severe fecal pollution in Massachusetts groundwater. As more houses are built and served by both private wells and private septic systems, strick adherence to existing sanitary codes should be emphasized.

In sedimentary and crystalline bedrock, movement of groundwater is along zones of fracture. Sewage and other polluted water that is discharged into rocks with fracture porosity may be transported for considerable distances before the water is purified, if at all. Some alluvial and glacial-outwash aquifers characterized by intergranular porosity are also prone to pollution for two reasons. First, in many places the depth to groundwater is relatively shallow in these aquifers, so there is little time for sewage effluent to percolate through the zone of aeration; maximum purification of water occurs during its passage through the zone of aeration above the water table. Second, many of the alluvial and glacial aquifers are in zones of groundwater discharge, which are chemically characterized by

slight reducing conditions; in this environment, the bio-degradation or organic material is low and conditions for fecal pollution are favorable.

Examples of fecal pollution in aquifers of fracture porosity underlying parts of Berlin, Conway and Granby, Massachusetts, are presented in the following sections. Berlin and Conway are underlain by crystalline rocks and Granby by stratified sedimentary rocks.

1) Berlin, Massachusetts (Motts and Saines, 1969, p. 46-47)

Berlin provides an example of fecal pollution of groundwater produced by the improper siting of septic systems.

Each house in Berlin has its own water well and sewage system. In areas of relatively high density (quarter-acre lots), the zone of aeration is insufficiently thick to effectively treat all the waste water; unpurified sewage waste is thus permitted to reach the bedrock. For the most part the underlying cyrstalline bedrock is characterized by low permeability along joints, but much higher permeability is present along a major shear zone which passes through the center of town.

Consequently, wells along this shear zone in the Carterville section of Berlin, had coliform counts which ranged from about 2 to 7.8 coliforms/100 ml, and in one case 240 coliforms/100 ml. A relatively high chloride content (5 to 160 ppm) and a high nitrate content (up to over 40 ppm) also suggested organic pollution. Part of this pollution is attributable to improperly functioning sewage disposal systems.

2) Conway, Massachusetts (Motts and Saines, 1969, p. 48-51)

Conway may be considered a typical example of a town, located on crystalline basement with poorly permeable cover mass, that has potential contamination hazards because of individual water supplies and sewage disposal systems that penetrate bedrock aquifers.

Much of the following information on Conway is from a study by Miller and Manning (1967), two graduate students at the University of Massachusetts, performed as part of a special problems project.

The Conway area is underlain by metamorphosed bedrock covered by semi-permeable to poorly permeable lake deposits and glacial till. The lake beds and till range in thickness from 5 to 10 feet in the western part of town to 150 feet along Main Street; because of their poor permeability, groundwater occurs primarily in joints and fractures in the bedrock. However, some groundwater development for domestic supplies also occurs in the shallow tills and lake deposits.

Groundwater in the Conway area may be subdivided on the basis of water chemistry into an upper water zone (within 100 feet of the land surface) and a lower water zone (deeper than 100 feet). The upper water zone is primarily in shallow bedrock, till and lake beds, whereas the lower water zone is primarily in bedrock. As table 4-3 indicates, there is a difference in water quality between the two water zones: the upper, or shallow, water zone has more chloride, higher total dissolved solids, and higher coliform content. Forty-five percent of all samples from the shallow zone, but only 10 percent of samples from the deeper zone, were positive for coliform organisms. The higher chloride content and higher percentage of coliform organisms indicate contamination of the upper water zone by sewage from individual septic tanks or from other sources.

Test	Shallow sources Range	Shallow sources Average	Deep sources Range	Deep sources Average
pH	6.4-8.1	7.20	6.7-7.95	7.50
Alkalinity	33-162	62.00	62-118	78.00
Hardness	40-260	85.00	70-130	95.00
Chloride	10-180	37.00	7.5-30	23.00
Nitrate	.5-3.1	.60	.2-3.4	.60
Iron	.03-.29	.13	.07-.22	.11
Totals dissolved solids	98-438	143.00	105-210	160.00
Turbidity	.3-4.00	.30	.3-1.5	.60

Notes:

1. All values in mg/l except pH, turbidity and color
2. Tubidity values in Jackson Candle Units
3. Where high values indicated definite local conditions, they were not used in the average.
4. Stream samples not used in Bacteriological percentages

Comparison of Ground-Water Quality Between Deep and Shallow Ground-Water Sources In the Conway, Massachusetts Area

TABLE 4-3

3) Granby, Massachueetts (Motts and Saines, 1969, p. 51-52)

The Granby area presents an example of fecal pollution in sedimentary rocks containing fracture porosity.

Each house in Granby has its own well and sewage disposal system. The western part of the town is underlain by sandstones and shales, neither of which have high bulk permeability. On the other hand, extensive joints and faults are present in both rocks, and shales. It is in these fracture systems that polluted water occurred in Granby.

State DPH records show that ten wells were tested for fecal pollution in the western part of Granby between 1960 and 1965. Four wells contained water of measurable coliform content and two contained water of potentially dangerous amounts: The coliform ranged from 2 to more than 23 coliforms/100 ml. Relatively high nitrate concentrations (1 to 12 ppm) also indicated aquifer contamination by sewage.

4) Canton, Massachusetts (Quincy Patriot Ledger, July 11, 1969)

To maintain the hygienic integrity of public water supplies, strict enforcement of the state and local Health Department regulations and careful monitoring of potential sources of contaminants are required.

On May 24, 1969, the Springdale well in Canton was ordered closed by the State Board of Health because samples of well water showed evidence of "bacteria characteristic of pollution."

5) Ipswich and Shawsheen River Basins (Morrill and Toler, 1973, p. 117-120)

Waste-water disposal through septic tanks and cesspools is common practice in many developments in the suburban Boston area. Such waste water percolates to groundwater reservoirs and eventually reaches streams increasing their dissolved-solids load by an amount that can be predicted from housing density.

Seventeen small drainage basins, all but one less than one square mile in area, were selected for study by Morrill and Toler. All are in the Ipswich and Shawsheen River Basins, in the communities of Andover, Burlington, North Reading, Tewksbury, Wilmington, and Peabody; all the basins are served by public water supplies, but none have municipal sewer systems. Many of the housing developments are located in the lowlands because the level terrain is easy to develop and the good soil permeability allows installation of on-site disposal systems. However, because the water table is only a few feet below land surface and about one-fifth of the area is subject to seasonal flooding, operation of on-site disposal systems is inefficient at least part of the year.

A positive correlation was found between housing density and the amount of dissolved solids in the base flow of streams. In the range of housing densities observed (0 to 900 houses per square mile), dissolved solids in stream base flow increased 10 to 15 mg/1 per 100 houses per square mile, the increase being attributable to the effluent from septic tanks and cesspools.

b) Pond Eutrophication

Increased water use means increased need for waste-water disposal. Waste water returned to the ground may add to available groundwater, but it frequently degrades its quality. Premature eutrophication of high value, fresh-water ponds by inadvertent fertilization is a common problem in Massachusetts, especially where the ponds are relatively shallow.

1) Billington Sea (SENE, GW Hydrology, p. 2-1, 4; 5-1)

Billington Sea in Southeastern Massachusetts is one example of premature pond eutrophication.

Ponds and bogs are features of the large groundwater reservoirs of Cape Cod and Plymouth county, and many smaller groundwater reservoirs elsewhere in southeastern New England. Many ponds and bogs of Massachusetts have developed in kettle holes that were formed during the melting of the last continental glacier in North America. As the ice melted, myriads of meltwater rivers deposited layers of sand and gravel around and over stagnant remnant blocks of melting ice. Later, when these blocks melted, they left great holes (kettle holes) in the sand and gravel. Many of the kettle holes contain ponds; many of the shallow ponds have filled with sediment and vegetation to become bogs. Today, the ponds are used for fresh-water recreation and their shores are favored residential sites. The ponds are like giant, shallow wells in the sand and gravel aquifer, and, under natural conditions, the water surfaces of the ponds may be regarded as surface exposures of the local water table (See Figure 4-2.)

In some instances a pond or bog is partly isolated from the aquifer by a layer of fairly impermeable sediment lining the bottom. In this case, surface water bodies respond slowly to changes in the water table elevation, and, conversely, the water table responds slowly to changes of surface water levels.

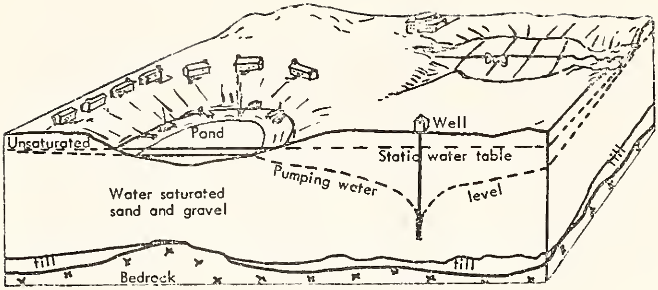


FIGURE 2

Relationship of the water table to ponds & bogs in kettle holes

Vertical exaggeration about 2X

Although natural eutrophication of a pond is generally slow, fertilization of ponds by sewage greatly accelerates the growth of algae and plants, which may fill ponds in tens of years rather than the thousands of years taken under natural conditions. Effluents rich in nitrate, organic material and perhaps phosphate from septic systems, cesspools, and surface discharges of surrounding homes eventually drain into the ponds (Figure 4-3). Algae and other plants nourished by these effluents clog the ponds, and the death and decay of algae produce an environment that is toxic to desirable pond life and cause obnoxious odors.

Billington Sea in Plymouth is an example of a fertilized pond. If pond ecology and property values are to be maintained, nutrient-rich waste water cannot be discharged into the ground near the ponds. Prevention of discharge, in general, is less difficult and expensive than reversal of eutrophication.

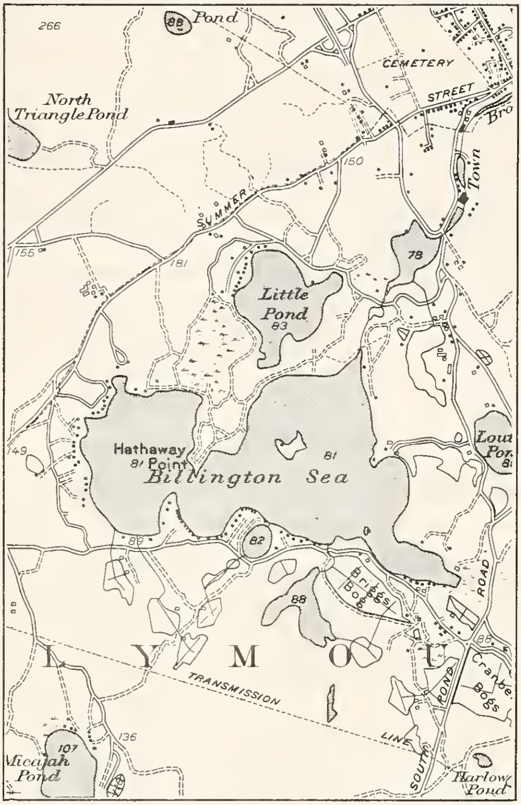
2) Morses Pond, Wellesley

Morses Pond is Wellesley's principal summer recreation area and only public swimming facility. The pond has been plagued with aquatic weed growth since 1964; on August 1, 1973, the public beach was closed for the season because of repeated and persistent algae blooms.

The pond, originally a much smaller body of water, had its surface level raised and area increased by a town-owned dam at Central Street. The north and northeast shores border on town property; private property, mostly residential development in Wellesley and Natick, abuts the pond in other areas. Nearly 79 percent of the watershed contributing to Morses Pond is outside Wellesley in the towns of Natick, Weston and Wayland. (Childs, 1971, p. 13)

The pond has an average depth of 6 to 7 feet with about 23 feet maximum. It is essentially a warm water pond that drains through Lake Waban to the Charles River. (Norfolk, 1972, p. 10)

In 1964 a bio-engineering study was undertaken to determine the cause of extensive aquatic week growth. (Cortell, 1964). The consultant's report found that (1) bacterial pollution was insufficient to create a serious problem at the town facilities; (2) general



Base from U. S. Geological Survey topographic quadrangle Plymouth, Mass., 1962

Figure 4-3

Freshwater ponds ringed by homes

contamination from detergents and chemicals appeared to result from a buildup of surface water drainage throughout the entire watershed system; and (3) the most acute aquatic weed problems existed in the man-made portions of Morses Pond. The report recommended (1) a 5-year aquatic weed control program; (2) a septic tank and cesspool survey by the Board of Health in the unsewered area of Wellesley, giving consideration to the extension of town sewerage to this area; (3) an educational program to inform residents of the effects of careless disposal of waste water and chemicals which might drain to the pond; and (4) inter-community cooperation with Weston and Natick to relieve the flow of nutrients through polluted streams to the pond.

Although the twon undertook a program of controlling aquatic growth through regular applications of copper sulfate, it did not extend the town sewerage system to the residential area abutting the pond.

Studies conducted in 1972 and 1973 by Mary M. Allen, Ph.D., of the Wellesley College biology department found that all parameters except phosphates were well within State standards for class B waters. She recommended that (1) the Town extend the sewerage system to avoid possible leaching of nutrients and bacteria from private subsurface sewage disposal systems into public waters, and (2) procedures should be investigated for the reduction of urban runoff pollutants for the purpose of lowering nutrient inputs that stimulate algae growth, including lawn and garden fertilizers. (Allen, Jan. 1973) (Allen, Oct. 1973)

When repeated treatments with copper sulfate in the summer of 1973 failed to relieve the problem of persistent algae blooms, an aeration program was initiated and the consulting firm of Camp, Dresser and McKee was engaged to study the problem of pond eutrophication.

TABLE 4-4

Results of Bacterial Samples Collected From Lake Holbrook

Lake Holbrook	Total Coliform	Fecal Coliform
End of Overbrook Road	9,300	1,500
Intersection of E.Shore Road and South Shore Road	24,000	91
North Shore Road	9,300	930
West Shore Road	24,000	930
End of Alder Street	240,000	46,000

Miles of Massachusetts Department of Public Health, Division of Environmental Health, Southeastern District.

3) **Lake Holbrook** (Lipman, 1973, p. 63-67)

Unrestricted encroachment by residential housing also has had an adverse effect upon Lake Holbrook. Effluent from residential subsurface sewage disposal systems enters the groundwater and then flows into the nearby lake. The accompanying table (Table 4-4) lists the bacterial results of five water samples taken by the Division of Water Pollution Control on 5 November 1970 from various points along the perimeter of the lake. Not only were the total coliform counts high (9,300 to 240,000 coliforms per 100 ml.), but fecal coliform, inhabitants of human and animal intestines, were also present (91 to 46,000/100 ml).

Table 4-5 lists the chemical oxygen demand (COD), biological oxygen demand (BOD), phosphorous, and Methylene Blue-Active Substance (MBAS) found in a lake sample. Taken together, these are positive evidence that dilute concentrations of domestic sewage were present.

TABLE 4-5

Results of Composite Sample From Lake Holbrook

Sample*	Concentration (mg/l)
COD	42.0
BOD	7.3
Total Phosphorous	0.3
Ammonia-N	1.2
MBAS	0.3
pH	5.9

*Samples collected by Division of Water Pollution Control, November 5, 1970.

3) Contamination by Leachate from Solid Waste Disposal Sites

Disposal of liquid or solid wastes may be a threat to water quality. Hydrologic conditions at prospective waste-disposal sites should be major factors in determining site suitability; such sites in prime groundwater recharge areas should be rejected by authorities if water quality is to be protected.

Regulations (Mass. Dept. of Public Health, 1971) for sanitary landfills are designed to prevent degradation of major groundwater reservoirs. Regulation 2.3 (states that it is necessary to "evaluate public importance of groundwater supply to be affected by the operation," and Regulation 2.4 states, in part, that "no area shall be considered or assigned, (c) which does not provide for protection of all sources of private and public water supplies." The use of recharge areas for sanitary landfills will result in contamination of groundwater unless leachate is prevented from entering the aquifer. The intent of the regulations is to prevent the deterioration of a resource of greater value than a sanitary landfill site.

Although good well sites have generally been avoided during siting of sanitary landfills, groundwater recharge areas have not always been recognized and avoided. Sand and gravel pits are commonly selected for sanitary landfill operations because of their low value for other uses and sometimes because of the availability of cover material. Unfortunately, many of these sites are in recharge areas for present and potential groundwater supplies.

The method of operating a landfill, as well as its location, can affect groundwater and surface water quality in a downstream direction. Klee (Vaughan, 1968) investigated 6,000 landfills and found only 6 percent met the minimal qualifications of minimal groundwater pollution, no open burning and adequate daily cov-

ering of refuse. In 1972 Raytheon Services Company (Raytheon, 1972, p. 1-6) reported 313 "dumps," 20 sanitary landfills and 11 transfer stations in Massachusetts and commented: "Of the approximately 300 landfills being operated only 6 fully meet the new standards. The remaining 97 (sic) percent are inadequate in varying degrees ranging from minor to major in terms of meeting new regulations."

Disposal of solid wastes in landfills is economical and convenient, but water percolating downward through the refuse becomes highly concentrated with dissolved solids of a particularly noxious character. Slight reducing conditions occur below the water table which tend to preserve and protect any leachate pollutants. A comparison of water standards, effluent from a municipal sewage treatment plant, and an analysis of leachate from a 2-to-6-year-old and and a 19-year-old municipal dump in Illinois are shown in Table 4-6 prepared by Kenneth Moon. (Moon, 1970, p. 22-23). On the basis of total dissolved solids, one gallon of the younger leachate contains 25 times the U.S. Public Health Service mandatory limits for drinking water standards; the concentration of iron is 400 times greater than the mandatory limit. In other words, one gallon of leachate could contaminate almost 400 gallons of iron-free water to a level unacceptable for public drinking water.

An example of groundwater pollution from a landfill is cited by Zanoni who describes a situation in Kreyfield, Germany, where about 700,000 cubic yards of refuse were deposited between 1913 and 1929. It took nine years for this leachate to be detected in the groundwater, by which time wells as far as a mile away had become polluted. Water in the polluted wells showed a chloride increase from 40 ppm to 260 ppm, and a hardness increase from 200 ppm to 900 ppm. These wells continued to be monitored, and it was found that the contamination lasted for about 18 years.

a) Palmer, Massachusetts: a landfill in bedrock (Motts, 1972, p. 34)

Locating a pollution free sanitary landfill in bedrock requires careful engineering. The bottom of the landfill must be sealed off from the bedrock by an impermeable layer, and suitable cover material often be imported from other localities; any leachate generated should be collected and treated. If these precautions are not taken, essentially unpurified leachate may easily enter the water table through fractures in the bedrock.

The Palmer landfill, near Bondsville, is an example of a refuse dump placed in bedrock without the precaution of sealing off the wastes and collecting the leachate. The solid waste has simply been dumped into an old railway cut in crystalline bedrock with minimal covering of the refuse; at Palmer as at other bedrock localities, it is difficult to find an adequate local source of soil cover. From one side of the cut can be seen a great mass of garbage and solid waste from which flows a "leachate stream" colored black by dissolved ferrous sulfide. Of course this potent leachate could raise havoc with surface and groundwater supplies.

b) Landfills in Groundwater Discharge Areas (Motts, 1972, p. 37)

With few exceptions landfills should not be placed in groundwater discharge areas; groundwater is commonly at or near the surface and many discharge areas are also areas of potential water supply.

The regulations of the Massachusetts Department of Public Health specify that the base of a landfill must be at least 4 feet above the highest water table. Nevertheless, some landfills and refuse

COLUMN NUMBER	1	2	3	4	5	6	7	8
IMPURITY	DRINKING WATER STANDARDS, PPM	HOUSEHOLD WATER STANDARDS, PPM	A SAMPLE WELL-WATER ANALYSIS, PPM	SECONDARY SEWAGE EFFLUENT, PPM	REFUSE LEACHATE, 2-6-YR-OLD DUMP, PPM	REFUSE LEACHATE, 19-YR-OLD DUMP, PPM	REFUSE POLLUTION POTENTIAL. SEE TEXT	D SEE TEXT
GROSS ORGANICS				52				
ORGANIC ACIDS					3950	40		
OXYGEN DEMAND				25	44,600	581	2800	
AMMONIUM				20			100	
ANTIMONY								
ARSENIC	0.01							
BARIUM	1							
BICARBONATE		150	12	100				28
BORON	20							
CADMIUM	0.01							
CALCIUM	200	40	6.1	15			645	45
CHLORIDE	250		5.4	75	1900	360	150	65
CHROMIUM	UNK.							
COPPER	1							
CYANIDE	0.01							
FLUORIDE	1.5		0.1					
HYDROGEN SULFIDE	1							
IRON	0.3	0.2	0.02		400	150	60	
LEAD	0.05							
MAGNESIUM	125	20	1.6	7			37	53
MANGANESE	0.05	0.05	0.08					
NITRATE	45		0	10				45*
PHOSPHATE				25			11	
POTASSIUM			0.4	10			250	
SELENIUM	0.01							
SILICA		10	12	15				
SILVER	0.05							
SODIUM	200	100	6.0	70	1651	554	110	27
SULFATE	250	100	21	30	820	140	80	53
ZINC	5							
TOTAL DISSOLVED SOLIDS	500	300	52	320	12,589	2524	4590	16

Water-quality standards & related data

Blank spaces represent absence of data, not "zero". Data in columns 1 to 6 are concentrations in parts per million by weight.

Col. 1 - Federal Standards for drinking water (U.S. Public Health Service, 1962)

* *Col. 2 - Standards for good water for general household use, as given by Davis & Dewiest (1966)*

* *Col. 3 - Analysis of a representative unpolluted soft groundwater in Mass., as reported by U. S. Geological Survey (1969, p. 298).*

* *Col. 4 - Average composition of effluent from municipal sewage treatment plants providing secondary treatment, expressed as amount of impurity over and above that already present in the municipal supply. (Weinberger et al., 1966).*

* *Col. 5 - Example of impurity concentrations in water associated with a two to six year old municipal solid-waste dump in Illinois. (Hughes et al., 1969, p. 84, installation 5B-CP, 9-21-67.)*

* *Col. 6 - Example of impurity concentrations in water associated with a nineteen year old municipal solid-waste dump in Illinois. (Hughes et al., 1969, p. 88, installation MM5b).*

* *Col. 7 - Estimated amount of pollutants leached in first year from a sanitary landfill, in units of gallon-ppm of pollutant per pound of solid refuse.*

* *Col. 8 - Theoretical population-density limits based on a sewage-disposal criterion as applied to an idealized model.*

* *Recommended by one author from study done on typical field data.*

dumps in Massachusetts have been placed below the water table; this was true in both Easthampton and Hubbardston. Some other landfill sites, including those of Lenox and Lincoln, are suspiciously close to the water table. In 1965 Rutland was considering placing its landfill in a valley site until it was shown that this same site was the best location for a potential groundwater supply.

c) Landfills in Groundwater Recharge Areas

Unfortunately many sand and gravel deposits at higher elevations are also not suitable for landfill sites because they are underlain by aquifers at depth or by aquifer-recharge areas.

1) Amherst (Motts, 1972, p. 37-39)

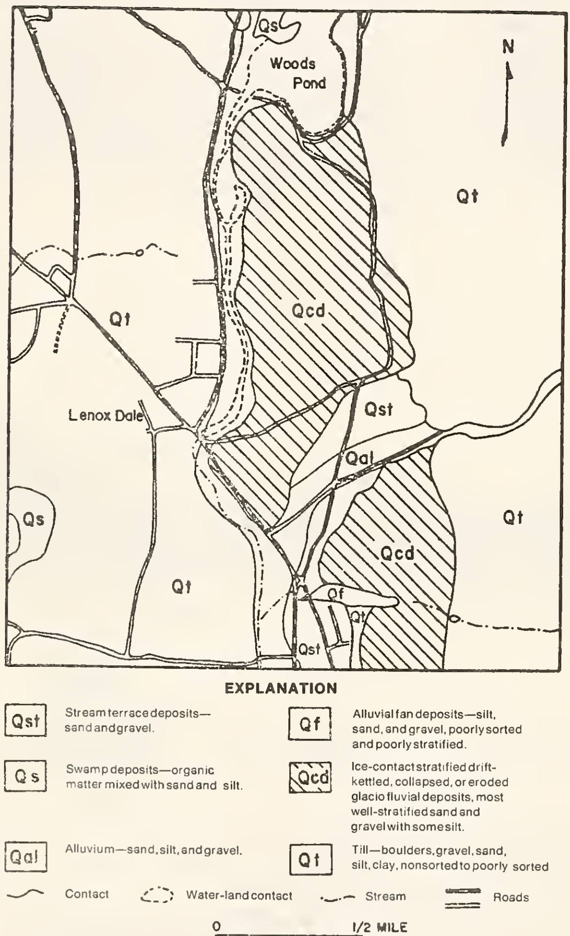
The location of the landfill in Amherst, which is situated in a groundwater recharge area, poses a constant threat to a municipal well sharing the same groundwater aquifer.

This landfill is located in sand and gravel deposits; one of Amherst's water wells, "the brickyard well," is located in the same aquifer about 3,000 feet to the east of the landfill site in a down-gradient direction (Figure 4-4). The landfill was developed before the brickyard well was drilled and before it was realized that the landfill was emplaced in a groundwater recharge area. Test drilling indicates that the sand and gravel have no large silt or clay confining beds; therefore, unrestricted movement of leachate occurs from the bottom of the landfill to the water table. As of this date, two observation wells drilled between the sanitary landfill and the

Figure 4-4

Topographic and hydrologic relation of sanitary landfill to some municipal wells at Amherst, Massachusetts.

brickyard well indicate a slight increase of chloride content but no major contamination, however, as already pointed out, significant contamination may take many years or even decades, as in the case of Kreyfried, Germany, described in a previous section. The initial increase of chloride may be significant because it is usually the first ion to migrate out of a landfill. Needless to say, Amherst officials are concerned and the two observation wells are being carefully monitored for pollution.



(geology modified from mapping by G. W. Holmes, Open-File Report U.S. Geological Survey)

FIGURE 5

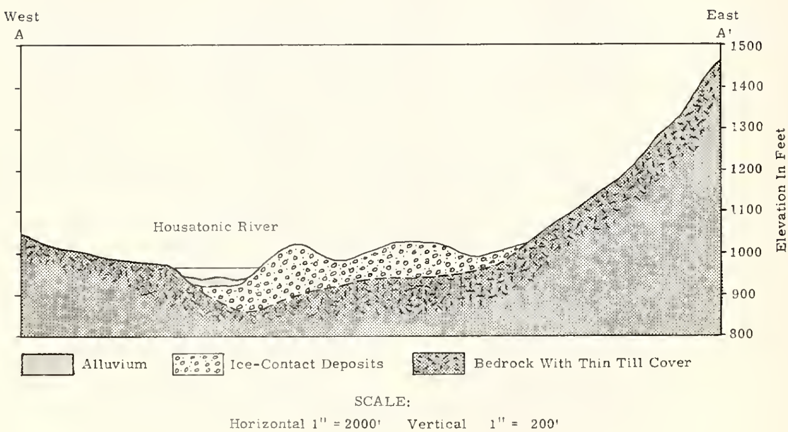
Location of high ground-water yielding deposits of stratifed drift in the Lenox-Lee area

2) **Housatonic Valley between Lenox and Lee** (Motts, 1972, p.39)

An extensive groundwater aquifer has been identified in an area which is under consideration as a landfill site.

A broad band of sand and gravel of ice-contact origin extends along the Housatonic Valley between Lenox and Lee. The deposits (Fig. 4-5, 6) are generally highly permeable and contain very large amounts of excellent quality water. The extreme northern part of the deposits by itself has a potential of about 6 mgd, more than enough water to satisfy all local communities and industry well beyond the year 2000.

Because of their proximity to Lenox and Lee, and because much of the surrounding area is underlain by bedrock and till, the sand and gravel ice-contact deposits have been chosen as landfill sites by Lenox, Lee and local industries. Although the present landfills on the southern extremity of the deposits have not as yet seriously endangered the ground water quality, improper siting of landfills in the future would threaten this potentially valuable water supply.



Generalized geologic and topographic cross section showing high ground-water yielding ice-contact deposits and their relation to bedrock and the Housatonic River

d) **Landfills Sited Near Streams** (Lea, Fergus Pearson, 1972, "Reeds Brook and its Effect on Receiving Waters", Civil Eng. Dept. Tufts U., cited in Lipman, 1973, p.54-59).

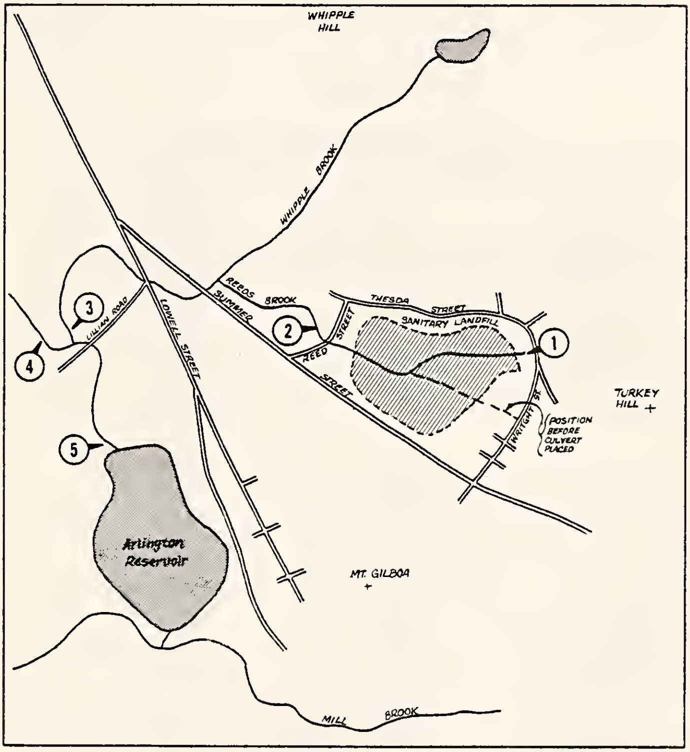
The aquatic life of surface waters can be destroyed by the drainage of groundwater polluted with the leachate from a landfill.

Figure 4-7 shows the location of the recently abandoned Arlington/Summer Street landfill. Passing directly through this landfill, encased in two corrugated steel culverts, is Reeds Brook which flows into the Arlington Reservoir. Table 4-7 lists the dissolved oxygen concentrations found in Reeds Brook; between August and November 1971 there was no dissolved oxygen in the brook after

***TABLE 4-7**

Reeds Brook Downstream of Summer Street Landfill
Arlington, Massachusetts

Date Sampled	Number of Samples	Average D Oxygen M (mg/l)	Normal Dissolved O (mg/l)
August 1971	4	0.0	9.2
September 1971	3	0.0	9.2
October 1971	2	0.0	9.4
November 1971	1	0.0	10.2
December 1971	5	1.4	11.3
January 1972	3	3.8	11.9



*** FIGURE 7**

Location of Arlington-Summer Street Landfill & Sample Stations

* Lea Thesis, "Reeds Brook and its Effect on Receiving Waters," 1972.

passing through the landfill. At the time of this sampling, the dissolved oxygen of Reeds Brook at Wright Street, upstream from the landfill, was sufficient to support abundant aquatic life with various species of bryozoans, leaches and limpits present. From the time the stream entered the landfill until it joined Munroe Brook, aquatic life was practically non-existent.

The consulting firm of Jason M. Cortell and Associates conducted an investigation of this area in 1969, and the only organisms found in Reeds Brook below the landfill were one species of chironomial worm, whose red color is characteristic of poorly oxygenated waters. The report further noted that the water leaving the landfill had a high chemical oxygen demand and a low (acidic) pH; it was heavily polluted with bacteria, iron, phosphorous and manganese (Table 4-8).

TABLE 4-8

Chemical Analysis of Reeds Brook

Test (mg/l except where specified	Location Wright avg	Street n*	Reed avg	Street n*
Turbidity (JTU)	22.0	1	108.0	1
Color-Appararent	65	1	405	1
Color-True (color units)	60	1	40	1
Alklinity (as $CaCo_3$)	50.0		285.0	1
COD	--	-	100.0	2
Chloride	142.0	1	228.5	1
Dissolved Oxygen	9.5	1	0.0	1
Iron	0.21	1	2.15	
Manganese	0.00	1	0.30	1
Nitrogen-Ammonia	0.15	1	22.50	1
Nitrogen-Nitrite	0.002	1	0.014	1
Nitrogen-Nitrate	1.178	1	3.261	1
pH	7.08	1	6.54	1
Phosphate-ortho	0.10	1	0.297	1
Bacteria-Coliform	800	1	0000	1

n* = number of measurements

Lea Thesis, "Reeds Brook and its Effect on Receiving Waters," 1972.

The water at station 2 (Fig. 4-7) was severely polluted even when station 1 was dry, suggesting a major source of pollution between the two stations, even though this section of the brook flows throug the landfill in corrugated steel pipes. This landfill was located on a wet meadowland surrounded by highlands; groundwater from the highlands passing through large sections of the landfill transported the dump leachate to the brook. Significant flows were observed downstream of the land fill even when no flow in the brook could be observed upstream. Apparently, fractures in the steel pipeline allowed Reeds Brook to be polluted by contaminated groundwater.

4. Other Pollution

Unwitting pollution of groundwater is common. Because aerated soil is a very different environment, biologically speaking, from saturated soil, purification processes occur in percolating water which do not occur in groundwater. Moon (1970, p. 18) cites three general conditions necessary for adequate purification in the zone of aeration:

1) The soil must have an active population of appropriate microorganisms.

2) The soil must be well aerated.

3) The residence time of the water in the aerated, biologically active soil must be sufficient for the necessary processes to proceed essentially to completion.

On the other hand, dissolved constituents in groundwater are persistent and generally do not disappear or become filtered out.

Moreover, unlike the pollution of surface water which generally becomes apparent in a short time, groundwater pollution may proceed for many years without being detected because of the characteristically slow rate of movement of water through the ground. Although artificial gradients created by withdrawal will increase groundwater velocity, in good aquifers natural velocities range from less than one to as much as twenty-five feet per day, with a normal value of one to eight feet per day.

Although water pollution control measures have traditionally been directed toward regulation of the quality of surface waters, it should be evident that the quality of groundwater is equally important, since ground and surface water are inseparable parts of the same natural system. Noxious and toxic substances which degrade the quality of surface water likewise degrade the quality of groundwater, regardless of the fact that our degree of regulation of surface waters vastly overshadows that of groundwater.

a) Iron and Manganese

Iron and manganese are major natural contaminants of groundwater supplies in Massachusettts. Throughout the state hundreds of test wells have encountered water that is unacceptable without treatment because of high concentrations of these metals.

In spite of the wide distribution of iron, one of the most abundant metals in the earth's crust, it is usually found in only minor amounts in natural waters. In alkaline surface waters its concentration seldom exceeds 1 mg/1; under acid or reducing conditions, both ground and surface waters may contain considerably more. Iron-bearing water stains laundry and procelain and at concentrations above 0.3 mg/l (the USPHS recommended limit) some persons may detect a bitter, sweet, astringent taste. (Motts and Saines, 1969, p.42)

Manganese, although rarely present in excess of 1 mg/l, imparts objectionable and tenacious stains to laundry and plumbing fixtures. The low manganese limits (0.05 mg/l) imposed on acceptable public water supplies stem from these aesthetic considerations rather than from toxicological reasons.

Although it is beyond the range of this report to discuss in any detail the field occurrence of iron and manganese a study by Motts and Saines (Motts and Saines, 1969, p. 42) found three significant relationships between excess iron and manganese and the geologic and geomorphic environment:

(1) Iron content increases with depth in aquifers of the crystalline basement.

(2) High iron content is common in many swamps.

(3) High iron content is common in places where organic material is interbedded with alluvial and glacial sediments near areas of groundwater discharge.

1) Blackstone River Basin (SENE, GW Mngt, Blackstone, p. 3-3)

During the dry summer months, much of the flow of the Blackstone River downstream from Worcester is sewage. This water contains a high concentration of organic matter, which creates a reducing environment, and is normally slightly acid. These physiochemical conditions favor the solution of iron and manganese; therefore, it is likely that the high concentrations of these elements occurring in ground water infiltrated from the river are, in part, due to the polluted condition of the river.

2) Crystalline basement (Motts and Saines, 1969, p. 43)

Water from some deep wells in crystalline bedrock have increased iron content with depth.

One example of this is a well drilled in the town of Lincoln, Massachusetts. At a depth of 40 to 50 feet the well yielded water with negligible iron and manganese; at a depth of 55 to 75 feet the iron and manganese content rose to 0.7 ppm; and at a depth of 85 to 105 feet the content rose to 10 ppm. This increase of iron with increasing depth also correlates with an increase in total dissolved solids.

In general, the deeper the water the longer it has traveled in the subsurface and the more it has reacted with the minerals of the porous medium.

3) Swamps (Motts and Saines, 1969, p. 43)

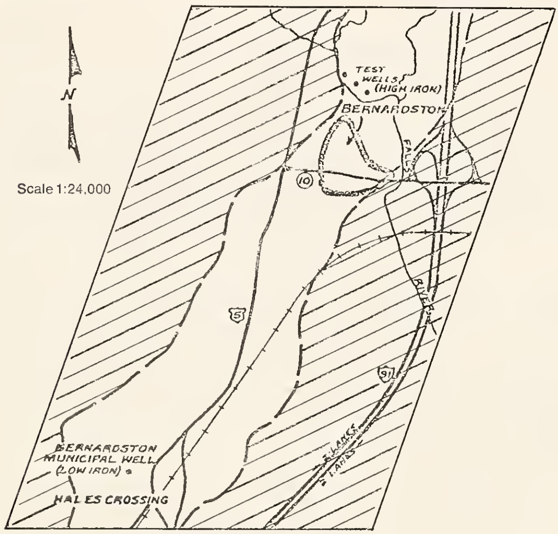
Iron occurs erratically in an aquifer underlying Lawrence Swamp southeast of Amherst, Massachusetts. Two wells located only 500 feet apart drew water from the same sandy-gravel aquifer, but the water produced from each well showed strikingly different quantities of iron (Angelo Iantosca, Mass. DPH, oral communication). Water from one well is used by the City of Amherst for municipal supplies, whereas water from the other well is unpotable because of the high iron content.

A test well near Lynnfield, Massachusetts, also encountered water of high iron and manganese content after penetrating 11 feet of peat.

4) Groundwater Discharge Areas (Motts and Saines, 1969, p. 43)

The groundwater in an alluvial discharge area near Bernardston, Massachusetts, also has a high iron content.

A buried valley, underlain by more than 100 feet of highly permeable sands, extends southwest through Bernardston along the general trend of the Falls River and on through Hales Crossing (Fig. 4-8). Three wells tapping the valley sands within 300 feet of the Falls River yielded water containing 5.5 to 8 ppm of iron, perhaps because they penetrated beds with a high organic content. On the other hand, two municipal wells drilled in the same valley, but farther from the valley axis, missed these organic rich beds and yielded water of low iron content.



EXPLANATION

Buried Valley Alluvium and Glacial OutWash

Bedrock and Higher Level Detrital Deposits

FIGURE 8

Generalized Geologic Map and Location of Wells
Producing High Iron and Low Iron Content in the Bernardston Area

Bog iron (SENE, GW Mngt., South Shore, p. 3-8, 9)

The presence of iron in groundwater in Hanover and other towns along the Massachusetts coast is not unexpected. Iron was mined in the region during colonial times, and in 1710 the Drinkwater Iron Works was established about 3 miles from the Hanover wells which now yield iron-bearing water. The iron ore, called bog iron ore, formed in the many bogs of the area because of their centripetal (central) drainage and both acid and reducing chemical environments. In fact, Hanover's wells in Tindale Bog are located in the drainage basin of Iron Mine Brook.

In the past, because of the naturally high concentration of iron and manganese in much of the groundwater of southeastern Massachusetts, it has been economical to simply not develop wells with iron-bearing water and to explore for water of better quality elsewhere. Now, however, because of increased demand and preemptive land use, additional sources of low-iron water are no longer available in many towns and development and treatment of iron-bearing water is necessary.

b) Toxic Metallic Ions

Toxic quantities of cadmium, chromium and cyanide have been detected in the highly polluted waters of the Tenmile River.

Cadmium has a high toxic potential, having been implicated in some cases of food poisoning and adverse renal arterial changes in human kidneys; a cadmium concentration of 0.20 mg/l has been found toxic to certain fish. On the other hand, there is an indication it might possibly be a dietary essential. The cadmium concentration of U.S. drinking waters varies between 0.004 and 0.06 mg/l, with a mean of 0.0082 mg/l; the U.S. Public Health Service mandatory limit is 0.01 mg/l. (APH Assoc., 1965, p. 32, 67-8)

Chromium salts are used extensively in industrial processes and chromate compounds are frequently added to cooling water for corrosion control. Chromium may exist in water in either the hexavalent or trivalent state, although the trivalent form rarely is found in potable water supplies. Hexavalent chromium, a potential carcinogen, has been reported in U.S. drinking waters in concentrations varying from 0.003 to 0.04 mg/l, with a mean of 0.0032 mg/l. The maximum permissible limit for hexavalent chromium established by the U.S. Public Health Service is 0.05 mg/l. (APH Assoc., 1965, p. 32, 122-3)

The presence of cyanide in water has a significant effect upon the biologic activity of the system: the threshold limit for fish is 0.1 mg/l as CN^-, and the microorganisms responsible for water purification are inhibited by a CN-content of 0.3 mg/l or above. The U.S. Public Health Service has established a recommended limit of 0.01 mg/l and a maximum permissible limit of 0.2 mg/l. (APH Assoc., 1965, p. 448-9, 32)

Degradation of the Tenmile River is due to the discharge of metal plating wastes and municipal waste water to the river. (SENE, GW Mgnt. Tenmile River, p. 3-1,2) Samples of Tenmile River water taken daily from August 4 to August 12, 1964, at five sites between the East Providence, R.I., Waterworks intake and a point above Harborville Dam, showed abnormal contents of toxic metallic ions. Both cadmium and chromium exceeded the U.S. Public Health Service maximum permissible limits for drinking water in some samples. The concentration of nickel exceeded the limit of 1 mg/l recommended for the element in some European countries. (McKee and Wolf, 1971)

The North Attleborough Board of Health has reportedly measured 2.5 mg/l cyanide in the Tenmile River.

c) Pesticides

Organic pesticides may be present in the ground and surface waters as the result of (1) direct application for aquatic insect or aquatic plant control; (2) rural or urban runoff; (3) residues occurring in groundwater from percolation of rainfall; (4) accidental or deliber-

Table 4-9

Maximum detected concentration of trace metals in Tenmile River water August 4 to August 12, 1964

Maximum concentration detected-mg/l	USPHS 1962	Rec limit-mg/l	Maximum limit-mg/l
Copper	0.70	1.0	-
Cadmium	0.11	-	0.01
Nickel	1.29	-	-
Zinc	0.55-	5.0	-
Chromium	0.12	-	0.05

ate discharge in manufacturing wastewater; (5) accidental contamination from drift when being applied to agricultural lands; and (6) discharge of wastes from cleanup of equipment used in insecticide application. The widespread use of pesticides has resulted in detectable residues in many major streams.

Adverse effects on water quality may result from the pesticide itself, the solvent carriers used in commerical formulations or chlorinated products of the pesticide. (APH Assoc., 1965, p. 224)

Cranberry Bogs (SENE, GW Mgnt., Taunton, p. 6-3)

The use of insecticides by cranberry growers is a potential source of contamination of groundwater. Most bogs are natural groundwater discharge areas; under normal hydrologic conditions, the likelihood of pesticides from bogs entering groundwater is minimal. However, if hydraulic gradients are reversed by heavy pumping, water containing pesticides may recharge aquifers.

In order to eliminate the possibility of contamination by pesticides, the Town of Duxbury, upon the advice of the Massachusetts Department of Public Health, purchased a cranberry bog that was upstream from a well site they wished to develop.

d) Phenols

Phenols are waste products of oil refineries, coke plants, and some chemical plants. Concentrations on the order of 0.01 to 0.1 mg/l are easily detected by odor or taste. Trace amounts as low as 1 microgram per liter (0.001 milligram per liter) can impart an objectionable taste to water following chlorination; this is the limit recommended by the U.S. Public Health Service (19962). (APH Assoc., 1965, p. 32, 229)

Because the removal of phenolic tastes from a water supply represents a challenging problem at the treatment plant, the Massachusetts Department of Public Health considers concentrations of phenols greater than 0.001 mg/l unacceptable for drinking water whenever it is encountered. A new well in Holbrook, Massachusetts, for example, within the first three weeks of operation was found to contain detectable amounts of phenol from a source 1500 feet from the well. Since there was no way of eliminating the contamination from the water, the $150,000 well had to be abandoned. (Coogan, Mass. DPH, oral communication) A potential groundwater source along Canoe River in East Mansfield was also rejected because chlorinated hydrocarbons were detected during a prolonged pumping test. (SENE, GW Mgnt., Taunton, p. 6-3)

Commonwealth Gas Company, Framingham (Miller, LCWA)

In December 1971, volunteer water quality monitors of the Lake Cochituate Watershed Association discovered a pollution problem on the Worcester Gas Company (now Commonwealth Gas Company) site in Framingham. Upon further investigation, it was discovered that at least 25 acres at the site had become impregnated with oil and tar to an average depth of ten feet, which is below the water table. A stream flowing through the site picks up gas odors and oil in significant quantities, transporting them to Beaver Dam Brook and Lake Cochituate, a major recreational lake. At the point of entry into Beaver Dam Brook, counts of 75 to 90 ppb (approximately .075 to .090 mg/l) phenol have been detected. Further downstream several towns with wells adjacent to the stream, including Billerica, have found that the resulting chlorinated phenols create problems of taste and odor in their drinking water supplies.

In terms of water quality, the problem at the Commonwealth Gas Co. site is compounded by an accumulation of industrial waste consisting primarily of wood chips coated with iron oxide which have been used to absorb sulfur from the gas. Surface runoff tends to produce pH readings in the stream as low as 2.0 to 3.0, probably caused by the combination of water and sulfur to produce sulfuric acid.

Commonwealth Gas has responded cooperatively to the problems it was creating: the dumping of wood waste has stopped and oil leaks appear to have been brought under control. As for the 25 acres of land impregnated with oil and tar, a consultant recommended an abatement plan which would isolate the area by surrounding it with trenches filled with impermeable clay and applying a layer of impermeable material over the entire site. The Watershed Association is concerned that this will not eliminate the problem of groundwater contamination.

e) Lead

Lead is a serious cumulative body poison. Natural waters seldom contain more than 0.02 mg/l, although values as high as 0.4 mg/l have been reported. The presence of lead in a water supply may be due to industrial, mine or smelter discharges, or the dissolution of lead plumbing. The U.S. Public Health Service maximum limit for lead in drinking water is 0.05 mg/l. (APH Assoc. 1965, p.32, 163)

A recent survey by the Massachusetts Department of Public Health indicated lead was not a problem in any public water supply in Massachusetts. The presence of lead in water from a public water supply in Massachusetts was invariably found to be caused by the dissolution of old lead pipe in a plumbing system.

Charlton, Massachusetts (Caldwell, unpub. case)

During 1971 the water from three private wells in Charlton, Massachusetts, became contaminated with gasoline; analyses by the Massachusetts Department of Public Health confirmed this fact. In the summer of 1972, blood samples from three children of one of the homeowners showed anomalously high lead levels. All three households now obtain drinking and cooking water from sources other than their own wells.

Although the presence of gasoline was tentatively ascribed by the Dept. of Public Health to surface runoff from nearby Route 20, the location of the wells with respect to a gasoline storage tank and the

geologic structure of the rocks between the tank and the wells are consistent with the hypothesis that the source of gasoline in the wells is the storage tank. Surface exposures of rocks indicate that the bedrock in the area consists of slaty and schistose rocks with a distinct cleavage, or parting, inclined downward about 20° to the east, from the gasoline station toward the three houses. The open spaces in rocks of this sort are principally related to the cleavage, and percolating groundwater would tend to follow such openings. The locations of the three private wells are in positions susceptible to contamination from an uphill direction. Although the service station owner has maintained that his storage tank area is not the source of contamination, investigators from the Massachusetts Department of Public Works and Division of Water Pollution Control feel that it is.

Samples of well water were analyzed for lead as well as for gasoline. Low-lead gasoline contains about one gram of lead per gallon of gasoline (about 264 mg/l), compared with two or three grams in regular and high-test gasoline (about 528 to 792 mg/l). Duplicate samples were sent to water-quality testing laboratories which produced results with varying degrees of correlation:

	First Sample May 1972 Total lead (mg/l)		Second Sample June 1972 Total lead (mg/l)
	Lab #1	Lab #2	Lab #2
House A	0.005	0.03	0.03
House B	0.003	0.06	0.01
House C	0.10	0.09	0.01

It is interesting to note the close similarity between the two analyses of the May sample from House C and the great disparity between the analyses of the other two houses.

5. Water Quality Problems of Cape Cod

Cape Cod and other regions in the Coastal zone of Massachusetts are subject to most of the water quality problems faced by other parts of the Commonwealth, plus a few which are specifically unique to this region alone.

(1) The Cape's heavy reliance upon groundwater as the sole source of fresh water and the inter-connected nature of the groundwater aquifer means that special precautionary measures need to be taken to guard against pollution of groundwater by effluent from septic tanks or sewage treatment plants, and leachates from solid waste disposal sites. The State Sanitary Code, as presently written, permits septic tank leaching fields to be sited where the groundwater table is only 2 feet below the field in areas of sand and gravel where the percolation rate is 2 minutes or less per inch. This rate of infiltration, however, means that septic tank effluent moves rapidly through the soil zone where purification is expected to take place. To preserve groundwater quality under conditions of rapid infiltration it would appear to be better practice to increase, rather than diminish, the required depth to water table.

Furthermore, secondary treatment with inland disposal of effluent through leaching beds is allowed under present State regulations for municipal sewage treatment plants. Since secondary treatment does not remove phosphate, nitrate, chloride or heavy metals, these impurities threaten to degrade groundwater quality if they are allowed to percolate down to the water table.

(2) The minimum required radius of protected land around a public supply well field is only 400 feet under existing state regulations. Pollutants can be drawn into a large well from distances far greater than 400 feet, especially in the highly permeable sands and gravels of Cape Cod.

(3) The problem of salt water intrusion into an aquifer is a problem which is unique to Coastal area. Hydrologists frequently compare the potential problems of Cape Cod with those which have been experienced by Long Island, New York, because the two regions are exceedingly similar both hydrologically and geologically. In Nassau County, Long Island, the disposal of sewage wastes by ocean outfalls and over-pumping for municipal and industrial purposes has caused the water table to drop 10 to 15 feet. In 1968 a salt water wedge was moving into the groundwater aquifer at a rate of several hundred feet per year, and in many parts of Long Island the glacial groundwater aquifer has been abandoned because the water is contaminated by sewage and other wastes. As pointed out previously in this report in the section on Water Quantity: Cape Cod, Provincetown has already been forced to shut down its wells within the town boundaries because of salt-water intrusion.

On the brighter side, the lack of manufacturing plants on Cape Cod means that groundwater quality is not degraded by the disposal of industrial wastes.

6. Summary

A comprehensive description of all the pollutants which might contaminate groundwater or surface water supplies is beyond the scope of this report. The subject of deep well injection of wastes has not been dealt with as a topic because of the unanimous agreement of the Committee that the unconsolidated deposits of Massachusetts are too shallow to permit disposal of wastes in this manner. The Department of Public Health concurs with this conclusion and refuses to issue permits for deep well injection of wastes.

The few cases of degraded water quality contained in this report are typical of many more which could not be included for lack of space. The principal point of this section on water quality is that pollution of groundwater can have a detrimental effect on the quality of surface water, and that degraded surface water can have a detrimental effect on the quality of groundwater, because they are both part of the same hydrologic system.

CHAPTER 5

Current Groundwater Law in Massachusetts

A: Common Law Groundwater Rights

Because there is no statutory arrangement in Massachusetts providing for allocation of rights to groundwater among private claimants, the subject is governed by past court decisions which were handed down as specific controversies arose.[1] These cases indicate that property rights to the extraction of groundwater are obtained through ownership of the overlying land. The overlying owner has been described as having absolute ownership of the percolating[2] water underneath his land. Unless motivated purely by malice, he may withdraw as much groundwater as he wishes, even if this results in a loss of water available on neighboring lands.[3] Use of water is not limited to the overlying land belonging to the pumper.[4]

1. Many of the leading decisions are from the nineteenth century. Although these cases stand as authoritative pronouncements for this jurisdiction, it should be noted that other states where litigation of groundwater rights has been more frequent have tended toward modifying some of the typical older doctrines as expounded in the early Massachusetts decisions. However, rather that speculate on the persuasive effect which out-of-state decisions might have on the resolution on future controversies before Massachusetts appellate courts, this discussion will confine itself to a presentation of the doctrines of the presently effective Massachusetts decisions. See page 68.

2. Distinctions drawn on some states between diffuse percolating water and underground water found in well-defined subsurface rivers have not been made in Massachusetts, probably because the occurrence of a subsurface river would be a geologic curiosity in this region.

3. The doctrine of absolute ownership, as developed in the Massachusetts cases, conforms generally with "English" rule of groundwater rights, so-called because it was set forth in the English case of **Acton v. Blundell**, 12 M. & W. Rep. 324 (Exchequer Chamber 1843). In fact, our earliest case antedates **Acton v. Blundell** by seven years. This is the case of **Greenleaf v. Francis**, 18 Pick, 117 (1836), in which the court did not expressly state that the overlying landowner had absolute ownership of groundwater but arrived at the same general result by stating that landowners may excavate and otherwise use their land as they please, without concern for incidental loss of groundwater by neighbors. Two limits of the landowner's operations were noted by the court. The owner may not withdraw sufficient water to cause land subsidence in adjoining properties, and he may not extract water purely for a malicious purpose. (This prohibition of malicious extraction is followed in most states adhering to the English rule. See Annot. 55 ALR 1385, 1395-98 (1928).)

   Acton v. Blundell, though not strictly a part of our common law, was influential in many U. S. jurisdictions, including Massachusetts; and its statements about absolute ownership, first cited with approval in **Benjamin Wilson v. City of New Bedford**, 108 Mass. 261, 265 (1871) subsequently became incorporated in Massachusetts groundwater doctrines.

4. **Wilson v. New Bedford, supra** note 3. Restriction of groundwater use to the overlying land is characteristic of another common law doctrine of groundwater allocation, the American rule, expounded in **Forbell v City of New York**, 164 N.Y. 527, 58 N.E. 644 (1900), and many other cases.

Though repeatedly described by Massachusetts courts as absolute ownership, the right to groundwater lacks one of the features normally associated with ownership, that is, the right to prevent interference with one's property. The overlying landowner, while permitted to withdraw as much water as his pumps can extract, cannot prevent activities on neighboring properties which interfere with the quantity of groundwater available to him. Thus, if his neighbor installs competing wells or performs land excavations which incidentally diminish or extinguish his supply, he has no redress in court. Because the right to groundwater does not include protection of supply, the Federal District Court indicated in one case that the common law right to groundwater gives no property right at all in the water itself.[5] Although this conclusion conflicts with the absolute ownership language in the state court cases, it serves to reach the same result, without the logical incongruity of an absolute ownership in property which cannot be protected from loss.[6] In any case, whatever the legal terminology chosen, the result is a substantially unlimited right for overlying landowners to capture and use groundwater.

The unlimited right to compete for groundwater does not, however, permit extraction of sufficient quantity to cause land subsidence on neighboring properties. This principle, announced in the earliest Massachusetts groundwater case[7] was reaffirmed as recently as 1964.[8]

Invasion of neighboring properties by water percolating from surface impoundments is also prohibited, as both older[9] and more recent cases indicate.[10] However, an artificial obstruction, such as a reservoir or well, which interferes with the normal escape of percolating waters from neighboring properties and thereby saturates or floods them is not a grievance subject to redress by the injured landowners.[11] This arbitrarry distinction probably results from traditional legal conceptions that actionable harm to land will be found when there is physical invasion by an extraneous tangible substance.

5. **Gallerani v. United States**, 41 F. Supp. 293 (1941).

6. The anomaly of absolute ownership of fugitive resources when supply is unprotected from competition by others has been the subject of comment by numerous courts. See **Williams v. City of Witchita**, 190 Kan. 317, 374 P. 2d 578 (1962), where the court stated that, "Much of the language in the cases pertaining to absolute ownership is **obiter dicta** and completely unnecessary to the respective decisions". See also **Knight v. Grimes**, 80 S. Dak. 517, 127 N.W. 2d 708 (1964), with comments to the same effect.

   In a case dealing with natural gas, where, as in the groundwater cases, the right to capture a fugitive resource had been phrased in terms of absolute ownership, the U.S. Supreme Court stated, in **Ohio Oil Co. v. Indiana**, 177 U.S. 201 (1899) that ". . .it cannot be that property as to a specified thing vests in one who has no right to prevent any other person from taking or destroying the object which is asserted to the subject of the right of property".

7. **Greenleaf v. Francis**, 18 Pick 117 (1836) (dicta)

8. **Gamer v. Town of Milton** 346 Mass. 617 (Mass 1964), which, though reasserting the absolute ownership doctrine, held that land subsidence caused by lowering of water tables when a pond was drained constituted actionable negligence.

9. **Benjamin Wilson v. city of New Bedford**, 108 Mass 261 (1871)

10. **Deyo v Athol Housing Authority**, 335 Mass 459')Mass 1957)

11. **Deyo v Athol Housing Authority**, 335 Mass 459 (Mass 1957)

Groundwater pumping by the process known as induced infiltration, can remove water from nearby surface watercourses. Under the legal scheme called the riparian doctrine, landowners abutting natural watercourses have rights to surface waters. Generally, these riparian rights are correlative rights based on reasonable use. Conflict can arise when surface water necessary to established riparian uses is lost through induced infiltration to pumpers. Such conflict was indeed the subject of litigation in four separate cases, but owing to the legal nature of the defendants in each of the cases, the opinions do not effectively dispose of the question of relative priorities when riparian parties are damaged by induced infiltration to groundwater users claiming the unlimited right to pump.

The defendants in three of the cases were publicly chartered corporations and in one, a municipality; all of the opinions turn on a finding that specific power to take water by induced infiltration was not to be found in the charters or enabling legislation of the defendants.[12] As a result, the question remains unresolved whether a riparian landowner could sue to prevent loss of water to a user taking by induced infiltration, although side comments in some of the cases suggest that the riparian owner might prevail.[13]

Similarly, we have no authoritative decisions stating whether a groundwater user may capture percolating water destined naturally for a surface watercourse. Dealing with a watershed as a hydrologic unit, it seems a trivial distinction whether groundwater had drained into a surface body and then was withdrawn by induced infiltration or whether it had been intercepted before arriving at the surface body at all. Still, the courts have spoken of such a distinction, and a side comment in at least one case[14] suggests that any landowner would be privileged to withdraw percolating water which was moving toward a surface watercourse, even if this interfered with riparian rights.

12. The cases are **Attorney General v. Jamaica Pond Aqueduct Co.**, 133 Mass 361 (1882); **Robert Cowdrey v Inhabitants of Woburn**, 136 Mass 409 (1884); **Proprietors of Mills on Monatiquot Rivers and others v Braintree Water Supply Co.**, 149 Mass 478 (1889); and **Hollingsworeth and Vose Co. v Foxborough Water Supply District**, 165 Mass, 186 (1896). In two of the cases, the plaintiffs were mill owners, and in another the plaintiff was a mill owner's associatiation. Motivation to litigate the unresolved questions may have decreased as the mill owners developed alterative sources of power and no new group arose with such economic dependence on undiminished flow of surface watercourses.

13. It is hard to escape the categorical force of such statements as, "If the water cannot be taken directly from Little Pond, it cannot be drawn therefrom by percolation. . . . It has often been held to be as complete a taking of the water as the withdrawal of it by pipes." **Proprietors of Mills v Braintree Water Supply Co., supra**, note 12, at 484. Similary, ". . . it is settled that the plaintiff has the same standing to complain of the withdrawal by percolation that it would have if the water were taken directly from the pond by pipes. . .". **Hollingsworth and Vose Co. v Foxborough Water Supply Co., supra,** note 12, at 190.

14. **Proprietors of Mills v Braintree Water Supply Co., supra,** note 12 The English case of **Chasemore v Tichards**, 7 H.L. Cas. 349 (1859) repeatedly cited with approval by Massachusetts courts, dealt with interception of groundwater moving toward and feeding a surface river. In that contest, the groundwater user prevailed over the riparian plaintiffs.

B. Allocation of Groundwater for Municipal Supplies

By the workings of various statutory provisions, the Massachusetts Department of Public Health plays a significant role in the development and allocation of groundwater supplies for municipal uses. The department has ". . . general oversight and care of all . . . underground waters used . . . as sources of . . . water supply . . ."[15] Supplementing this expansive mandate, other statutory provisions give more specific powers to the department. The department is to consult with municipalities as to the most appropriate sources of public water supply and the best methods of assuring purity of water.[16] Furthermore, when lands and sources of water are taken by towns for public water supply, prior approval of the department must be obtained.[17] Similarly, before any lands may be taken by a municipality for preservation of the purity of public water supply, approval of the department must be obtained.

By these statutes, the General Court has granted to towns the right to acquire for municipal supply groundwater sources within their limits, a power which hitherto had been granted only by special acts from time to time as the need arose. However, this power is to be exercised only with the advice and approval of the Department of Public Health. As part of its approval process, the Department of Public Health determines the extent of competition which the new well will have with other users. If competition will occur, the Department may specify pumpage rates and, for both the new and existing wells, minimum distances of separation between the wells. This is in effect an allocation of groundwater between the new well and previously existing users. These same functions are performed by the Department of Public Health in its approval process when municipalities acquire groundwater sources outside their limits, pursuant to special acts of the legislature. The allocation which takes place when a municipal well is involved not only regulates competition between that municipal well and other municipal wells but also between the municipal well and competing private users, because the Department regulates the continued maintenance or new construction of wells which would deleteriously affect existing sources of public supply.

C. Groundwater Pollution

Chapter 546 of the Acts of 1973 initiated a new regulatory program in the area of groundwater pollution. Discharge into groundwater of polluting matter originating from point or major nonpoint sources is subject to civil and criminal penalties unless a permit is obtained from the Division of Water Pollution Control.[18] Every permit is to specify effluent limitations, compliance deadlines, and various other terms.[19] The effluent limitations are, as is the case

15. Chapter 111, section 159, Mass. General Laws

16 Chapter 111, section 17, Mass. General Laws

17. Chapter 40, section 39B, Mass. General Laws

18. Ch. 21, § 42, Mass Gen Laws, and also definitions, § 26A, for "pollutant" and "waters". It is crucial, when reading the substantive provisions of the act, to refer to the defined terms to ascertain the true coverage of the act. "Point" and "major nonpoint sources" are not defined terms.

19. Chapter 21, section 43(7), Mass. General Laws

with surface water pollution, the key factor which will determine the extent of pollution permitted. The Division of Water Pollution Control is required to establish these limitations by administrative action.[20] The effluent limitations promulgated by the Administrator of the U.S. Environmental Protection Agency under thhe Federal Water Pollution Control Act Amendments of 1972, P.L. 92-500, need not necessarily be adopted as the standards governing the Massachusetts program regulating discharges into groundwater, for the federal permit program does not deal with groundwater.[21]

In addition to the new authority which has been granted to the Division of Water Pollution Control to regulate groundwater pollution, there continues the long-standing authority in the Department of Public Health to take action to preserve the purity of ground waters used as the sources of public water supplies. In this regard, the general oversight which the department has over groundwaters is supplemented by various provisions making pollution of public water supplies illegal.[22]

D. Land Use Control Relating to Groundwater

Under Chapter 40, section 41, Mass. General Laws, municipalities may acquire by purchase or eminent domain ". . . lands . . . within the watershed of any . . . source of water supply, which . . . [the department of public health] . . . may deem necessary to protect and preserve the purity of the water supply." It appears that this is a grant to municipalities to take lands by eminent domain even through the lands may be outside their limits.[23] The Department of Public Health, by its authority to withhold approval of new sources of public water supply, can effectively require municipalities to exercise this authority to acquire title to sufficient land to protect the purity of well waters used for public supplies.

In addition to the power to acquire actual title to land for the purposes of protection of water supplies, municipalities may have certain powers not requiring compensation to private landowners by which land use can be controlled in the interests of groundwater management. Under the zoning enabling statute, municipalities may enact zoning regulations which "conserve health," "facilitate the adequate provision of . . . water," and "encourage the most appropriate use of land."[24] Under a liberal reading of these provisions,

20. Chapter 21, section 27(6), Mass. General Laws

21. Notice, however, that for a state-run permit program for surface-water discharges to be approved by the Administrator of the Environmental Protection Agency, the state must have "adequate authority. . . to control the disposal of pollutants, into wells . . ." P.L. 92-500 § 402(b)(1)(D). See also Senate Report 92-414 (1971), discussing why the Congress chose not to regulate groundwater pollution and why it chose to require that states be able to control deep well injection.

22. Chapter 40, section 39G; Chapter 111, § § 159, 162-167, Mass. Gen. Laws

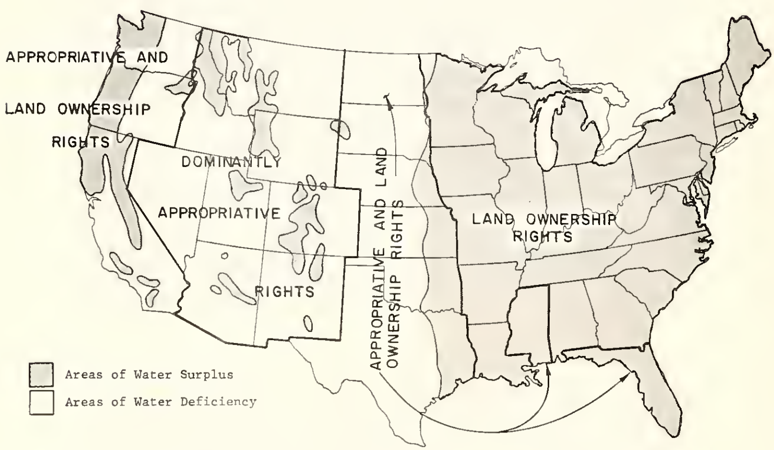
23. Chapter 40, § 39B, granting towns authority to acquire sources of water supply, expressly limits this power to the boundaries of the town. The failure to provide this limitation in § 41 surely provides basis for the inference that territorial limitations were not to apply, when powers were being exercised under § 41.

24. Chapter 40a, § 3, Mass. Gen. Laws. See also similar provisions in the area of planning and subdivision control, Chapter 41, § 81-M.

ample power can be found for land use regulations that protect the geologic structures which are essential to the natural cycle of groundwater movement, but there is room for reasonable disagreement as to the scope of the issues which these statutes actually intend to cover.

Further control of land use which threatens harm to groundwater supply is to be found in the wetlands protection statute. Proposed alterations of wetlands which are significant to the groundwater supply are subject to the permit procedure outlined by statute. This procedure authorized the imposition of permit conditions after public hearing before local officials. Local permit actions may be superseded in individual cases by hearings before the Commissioner of Natural Resources. In either case, permits are to reflect conditions which protect the value of wetlands in their relation to groundwater supply.[25]

25. Chapter 131, §40, Mass. General Laws.



DOMINANT WATER RIGHTS DOCTRINES

Source: Water Information Center, Inc., Water Atlas of the United States, 1973.

CHAPTER 6

Economic Aspects of Groundwater Management

Groundwater management, insofar as it relates to the allocation of a resource among competing demands, presents issues which can be subjected to economic analysis. It is the purpose of this chapter to provide no more than an introduction to the major elements of economic theory that have a bearing on problems of groundwater policy. Readers with a technical background in economics are urged to consult references cited in the footnotes.

I: Externalities

Users of a resource such as water are generally pictured as applying the resource to their most urgent and valuable uses first. If more water is available after the most valuable uses have been satisfied, then water will be applied to increasingly less valuable uses in sequence. If the cost of water to the user remains at a constant figure per unit, or, as is more likely, begins at some point to increase as more is consumed, sooner or later the uses being served will be less valuable than the water being consumed. If the user is behaving in a economically rational manner, he will stop at the equilibrium point where the cost of consumption of the last unit equals the benefit.[1] However, traditional pricing policy for water often reduces the rate with increasing use, shifting this equilibrium toward higher consumption.

In some cases, consumption of a commodity generates costs, called externalities, which the user does not pay. Groundwater use is characterized by externalities. Pumping by a given user can increase the costs of pumping by other users in the aquifer. Consumptive use of groundwater will cause a loss of water volume in related surface water systems, thereby inflicting costs on persons who use the surface water.

From society's point of view, resources will be misallocated if an individual groundwater user need not consider externalities when computing the cost of obtaining a unit of water. Because the groundwater pumper is obtaining his water at a cheaper price than the full social cost, he will be encouraged to use more of it than is socially desirable.[2]

The external costs inflicted on society may fall heavily on a few others (e.g., the downstream mill owners in the induced infiltration cases, who, if they can act cohesively, may have sufficient stake to incur the expense of seeking legal redress and shifting costs to the water user). But in many cases the individual disutility suffered is small, and only when multiplied by the number of persons harmed

1. An excellent discussion, both in layman's terms and with a more technical exposition, of the equilibrium of marginal value in use is to be found in Hirshleifer, DeHaven, Milliman, **Water Supply: Economics, Technology, and Policy**, U. Chicago Press (Chicago, 1960)

2. The problem of externalities has received considerable attention from contemporary economists. In the area of water pollution a now classic analysis is Kneese and Bower, **Managing Water Quality: Economics, Technology, Institutions**, Johns Hopkins Press, (Baltimore 1968); in the area of water resource allocation, the reader is referred to Hirshleifer et al. **op. cit.**, note 1, and Alan E. Friedman, "The Economics of the Common Pool: Property Rights in Exhaustible Resources", 18 U.C.L.A. Law Review 855 (1971), and sources cited therein

will aggregate to a larger sum. In this case, generally, no single individual has sufficient stake in the problem to seek redress of the grievance. Instead, collective action, characteristically by government, is necessary to rectify the harm.

Various suggestions have been made as to the form which such governmental intervention should take. Some authors suggest that a tax can be devised for groundwater use which would be equal to the externalities which such use generates. The individual pumper would then be faced with the full social cost of his consumption. This plan would only be effective if the dollar amount of the external social costs could be accurately estimated by the taxing authority. At the present state of knowledge, the probabilities of such accurate estimates are small. The same pragmatic objection infects another possible scheme, the sale of water by a single water supply agency at a uniform price reflecting social cost.[3]

The problem of externality and overutilization can be attacked by the use of non-economic solutions as well. Limits on withdrawals can be established, thereby making a non-market allocation between a pumper and other competing interest. For instance, pumpers can be prohibited from withdrawals which will lower surface waters below a fixed level. This in effect prevents the pumper from inflicting external costs on surface water users.[4] It must be recognized that this sort of non-market allocation would only by chance resemble the market allocation that would take place if all externalities were accurately reflected in the costs which the groundwater user faced; but at least non-market controls would curtail the uncontrolled infliction of harm on society at large by enterprises which incorrectly value the resources they consume. Whatever devices are eventually established to cope with the problem, externalities should be recognized as a significant distortion that should be of concern to authorities concerned with the efficient allocation and use of water resources.

II: Property Systems in Water Rights

Economic analysis points to certain features which a system of water rights should have to promote efficient resource allocation.[5] To the extent that the policy-maker disagrees with the assumptions of economic analysis, he may properly view the economic norms with circumspection; but it is important to have an overall understanding of the features of an economically desirable system.

Proper allocation of finite resources implies that more valuable uses are satisfied before less valuable ones. This is served by economic norms requiring ease of transferability and certainty of tenure.

3. Similar plans are discussed by Hirshleifer et al. and Friedman in the works cited in note 2.

4. For example, Washington state prohibits appropriations from watersheds which will impair certain values in surface water resources such as wild-life and recreation. Rev. Code Wash., 90.22.010 and 90.22.020.

5. More thorough analyses of the issues discussed in this section can be found in Hirshleifer et al., **op. cit.**, note 1, and Trelease, "Policies for Water Law: Property Rights, Economic Forces, and Public Regulation," 5 Nat. Resources Journal 1 (1965); Ciriacy-Wantrup, "Water Economics: Relations to Law and Policy", Ch. 5 in Vol. 1 of **Waters and Water Rights**, (Clark, ed.) 1967; National Water Commission, **Water Policies for the Future** (Washington, D.C., 1973) at pp. 247ff.

If it is assumed that more valuable uses are supported by greater purchasing power behind them, then in a competitive market situation, the more valuable uses will attract resources by virtue of this purchasing power. If property rights in a commodity are not freely transferable, this tendency of resources to gravitate to their most valuable uses is frustrated. Even if resources were originally allocated to their most valuable uses, changes in preferences and technologies might alter the desirability of the original allocation. If resources cannot be reallocated to conform with changing needs, resources will not be utilized to their utmost productivity.

Certainty of tenure plays a crucial role in support of transferability. If firm rights to a resource cannot be obtained, then capital investment needed for resource exploitation will be discouraged. Similarly, if a firm right cannot be transferred, then a potential buyer will not see a right worth purchasing. As a result, economic analysis points toward a system of fixed, fully transferable rights to a specific quantity of water, good for a long enough period that capital investment can be recovered when made in dependence on the water right.

Present common law groundwater rights in Massachusetts do not fully conform to this ideal picture. The basic dictate of transferability is probably met because groundwater, once pumped, can be sold to other users off the overlying land. But the rule of capture prevailing in this state means that certainty of tenure is lacking. It is not obvious that this has operated as a significant disincentive for investment, for import of surface water has served to alleviate competition in groundwater resources in many areas. Nevertheless, as demand on water supplies increases throughout the Commonwealth, the theoretical weakness resulting from uncertainty of tenure may assume a larger significance.

Existing Deficiencies and Proposals In Laws And Institutional Arrangements

RECOMMENDATIONS

Problems; The following list of problems, summarized from those presented earlier in this study, are addressed in the text of recommendations in this chapter.

1. Consumptive use of groundwater may significantly degrade uses and rights in related surface water systems. (See Watershed Management and the Concept of Streamflow Protection)
2. Some groundwater systems are subject to natural limitations on withdrawal which have not been fully analyzed. Unregulated consumptive use by some private users could threaten to aggravate problems of safe yield. (See A Permit Program, Comprehensive Allocation, The Option of Critical Area Management, and Conservation of Water)
3. The existing system of common law groundwater rights in Masachusetts was developed when knowledge of groundwater was limited. The common law can be improved in light of modern knowledge and technology. (See Modifications of the Common Law).
4. Pollution on groundwater and hydraulically connected surface water systems is a frequently recurring problem, with regional as well as local impacts. The problem results from road salt usage, concentrations of septic systems, and municipal and industrial waste disposal practices. (See Groundwater Pollution)
5. Land use practices (including paving and other construction, gravel mining, and waste disposal) can significantly impair recharge areas. (See Land Use Policies for Recharge Zones).

Watershed Management and the Concept of Streamflow Protection

Except for unusual geologic areas, such as Cape Cod, the most meaningful geographic unit by which to manage water is the watershed. Management restricted to a smaller scope can fail to take proper account of influences which water resource use in one area can have on other areas within the same watershed. Because in Massachusetts groundwater basins and surface watersheds usually coincide, conjunctive management of the two as single geographic units is simplified.

One of the major issues in the management of watersheds is that of uses which cause a net loss of water to the watershed. These are termed consumptive uses. Irrigation is to a degree a consumptive use. A wholly consumptive use occurs when waste water is sewered and exported from the watershed. Significant consumptive use permanently takes water from the surface watercourses of a watershed and lowers their value.

The Commonwealth should consider the desirability of regulating consumptive uses which significantly disturb the integrity of surface waters. The National Water Commission has recently recommended that minimum levels for streams and lakes be protected

"in order to promote public health, safety, and welfare, to safeguard private investment made in reliance on continuing streamflows and lake levels, and to protect the public interest in fish, wildlife, recreational, esthetic, and ecological values."[1]

A few states have enacted legislation giving some protection to minimum levels in surface waters. In New Jersey and Mississippi, permits for consumptive use of surface waters are not to be granted for uses which interfere with historically determined low flows.[2] In addition, the permit-granting authority in New Jersey must consider whether proposed uses will so reduce dry season flows as to "unduly injure public or private interests,"[3] In Iowa, uses of surface waters which deplete flows to the point where it is "harmful to the public interest" are prohibited.[4] In Florida, the Department of Natural Resources may reserve from consumptive use either by ground or surface water users such quantities which "may be required for the protection of fish and wildlife or the public health and safety."[5] Similarly, in Washington, the Department of Water Resources may reserve levels necessary for protecting "wildlife resources, or recreational or aesthetic values" of surface waters.[6]

The National Water Commission has suggested that, although protection of streamflow is desirable public policy, complete protection of streamflow under all conditions may be too extreme a program. The Commission instead recommended that all important values in streamflows be protected during normal conditions, but that only critical needs be protected during times of overall water shortage.[7] This more flexible program may well recommend itself to policy-makers in Massachusetts.

It is evident that significant scientific expertise must be brought to bear in the determination of protected surface water levels and the amount of consumptive use which would not impair these levels. Accurate determinations can be made only after thorough watershed-by-watershed research and analysis. Data accumulation and processing techniques must be adequately developed before these determinations can be properly made. The United States Geological Survey maintains a network of streamflow gaging stations which provides a useful inventory of basic data; but substantial supplementary data and analysis would be necesary. Ideally, the raw data should be integrated into decision-making formats, such as computer simulations of river basins.

This research and analysis must be adequately supported with funds and manpower to produce useful results. It is true that most scientific decisions are made at some level of uncertainty. In Iowa, for example, determinations of minimum streamflows are permitted to be made in the presence of less than complete data.[8] But reasonable accuracy is necessary to provide fairness to regulated users; and, of course, increased accuracy provides greater assurance that a regulatory program achieves its goals. It is possible to

1. **Water Policies for the Future** (Washington 1973), at p. 287
2. New Jersey Stat. Ann. § §58:1-35, 58.1-40; Miss. Code § §51-3-7(3) and (4).
3 New Jersey Stat. Ann. § §58.1-39.
4 Iowa Code Ann. §455A. 1, 455A.22.
5 Florida Stat. Ann. §373.223
6. Rev. Code Wash. § §90.22.010, 90 22.030
7 **Water policies for the Future** (Washington 1973) at p. 287
8 Iowa Code Ann. §455A.1

undertake a regulatory program using temporary permits based on incomplete data, such permits to be subject to change or revocation after full study of a watershed.[9] The cost of such a program is an uncertainty and poses a degree of unfairness to users who lose their permits.

A PERMIT PROGRAM

It seems inescapable that if any type of public control is to be exerted over the development of water resources by both private interests and competing municipalities, some sort of permit program must be initiated. Both private users and municipal and other public users should be subject to permit requirements in a single, integrated permit program. Domestic wells could be generally exempted in most watersheds, because domestic consumption is usually small and the burden of regulating it is substantial.[10] A permit program would serve one or more of at least three possible purposes: information gathering on patterns of water resource use, protection of surface waters, and allocation between competing uses. Discussion of the allocation role will be reserved for a later section of this chapter.

In order to provide basic data for water resource planning, well log reporting at the completion of each well and periodically thereafter should be a stipulation of every permit. Appropriate penalties, including revocation of the driller's license, should be able to be assessed for failure to obtain a permit or comply with its provisions.

For implementation of a program of protection of surface waters, the permit should be required prior to drilling of the well. Permits should be granted only if the consumptive use will not impair minimum levels in surface waters which are necessary to preserve important values. In order to make this judgment, a hearing process should be available. Many permits may be routinely granted without a hearing, but a hearing should be conducted on the initiative of the applicant, if his permit is denied, or on the initiative of the Commissioner of Natural Resources, Commissioner of Public Health, any municipality adversely affected, ten citizens resident within the watershed who can make a threshold showing of probable environmental harm, or any private person or entity able to show special harm to himself. A decision not to have a hearing, or a decision, after hearing, to issue or not to issue a permit should be subject to judicial review. It may be advisable to make the hearing procedure mandatory under certain circumstances, such as permit requests by users above certain size, for example, 100,000 gallons per day.

At the hearing, the burden of proof should be on the applicant to demonstrate that his proposed consumptive use will not impair important public values in surface waters of the watershed. In this way, until data are accumulated for the whole state by public agencies, decisions can be made on the basis of the best available knowledge, without overextending the resources of the agency conducting the hearing. Allocation of burden of proof on the party proposing the use is not as severe as it may at first seem. The users

9 Oklahoma Stats., Ch. 82, § 1020.11 (B)

10. Regulation of domestic uses is rare in states which issue permits for water use. Besides the realization that such regulation would be unproductive there is a policy in many states that these uses have an ultimate priority over all other competing demands on water resources. Hence, their regulation is not called for

subject to regulation will generally be larger enterprises, with the financial backing to support a factual investigation; probably, in fact, significant study of the area will have been conducted by the user relative to siting of wells, safe yield and so on.

In support of the proposal on burden of proof, it is appropriate to note that certain states presently place the burden of proof on the applicant is some or all situations. For example, in Florida, "the applicant must establish that the proposed use of water: a) Is a resonable-beneficial use . . . b) Will not interfere with any presently existing legal use of water; and c) Is consistent with the public interest."[11] In North and South Carolina, the burden of proof at permit hearings is on the applicant if he calls for a hearing.[12] In North and South Carolina, Georgia, and New Jersey, applicants have the burden of proof that their proposed uses are not consumptive uses if this is a fact that they wish to demonstrate.[13]

The permit program should initially be the responsibility of a single state-level agency[14] However, consideration should be given to the establishment of watershed management agencies (or in the case of Cape Cod, a regional water management agency), to be governmental bodies composed of representatives of all the communities within the watershed. In instances where issues are primarily local in scope and management of the water resources by a state-level agency would be inappropriate, the communities could form watershed management agencies which could determine minimum streamflows, run the permit program, and perform associated responsibilities. These agencies should have access to data and technical assistance from the Department of Natural Resources and the Department of Public Health as necessary in order to perform their functions, and their decisions would be subject to review and confirmation by the lead state agency.

Such alternatives as have been discussed in this section should serve as the basis of further study and discussion. In considering all of the various alternatives and options available to it, the Commonwealth must also be aware of the political and practical problems in any proposal to regulate water use by a permit program, particularly if, as is usually the case, the watershed basins are not contiguous with existing political boundaries. Before any new agencies are created or laws and regulations adopted, a most careful and expert study should be made to define the issues and the areas of conflict. Suggested answers should be at hand and a suggested program outlined.

Public education is an essential part of public acceptance of such a program.

In addition the legislature must be sufficiently convinced of the necessity of change to make an adequate commitment of support. Nothing could be more disheartening than to enact more laws and embark upon an ambitious program, only to have the program fail in its execution because of inadequate staffing or funding.

11 Florida Stats. Ann. §373.223

12 Gen. Stats. N.C. §143-215.15 (f) (7); Code of Laws of S.C., §70-36 (f) (7)

13. Gen. Stats. N.C. § 143-215.15 (b); Code of Laws of S?C?. § 70-36(b); Ga. Code Ann. §17-1106 (b); N.J Stats. Ann. 58:1-38.

14 It is desirable that permit applications be made in sufficient copies that notice be sent to other agencies with an interest, including municipal conservation commissions.

Modifications of the Common Law

The common law principles of "absolute ownership" governing the allocation of groundwater among private claimants are based on outmoded conceptions of hydrology. The older cases seem to treat groundwater as a static mineral. For example, in *Wilson v New Bedford*, the court declared that, "The percolating water belongs to the owner of the land, as much as the land itself, or the rocks and stones in it.."[15] By grouping water with the soil and minerals of the land, the courts failed to give proper emphasis to the dynamic nature of groundwater's presence in the earth. Water is found in the ground only during one phase of the hydrologic cycle; and its constant movement through the cycle means that consumption by well-users will have effects off the property where the water has been pumped.

Even when the courts recognized that groundwater pumping could affect other parties, they concluded that the movements of groundwater were so unascertainable as to render impossible any efforts to allocate it.[16] As a result, the landowner's package of rights in groundwater differs from his rights to surface water. His rights to use of surface water are limited to reasonable use, determined by the co-equal rights of other landowners abutting the same watercourse. His right to groundwater is limited only by how much he can extract.

The ground and surface waters of a watershed are in fact a single hydrologic unit. No persuasive reason presents itself to explain why, in light of the contemporary knowledge of hydrology, two systems of law should govern this single interrelated resource.[17] Heavy pumping visits harm on riparian owners and on other groundwater pumpers in ways that are now understood and are calculable. The failure to provide legal redress for these harms allows a groundwater pumper to wrest away, without compensation, valuable rights hitherto exercised by others. Consideration should be given to legislative enactments which would rectify this deficiency. Legislative change could take the form of allowing riparian owners[18] and prior groundwater users to sue for redress of harms caused them by another party's new or expanded usage of water. An even more desirable response may be to incorporate a rational system of allocation into a program of basin-wide planning and permits for water use, as outlined elsewhere in this chapter.

15 108 Mass. 261,265 (1871)

16 Where the movement of water through the ground was more clearly ascertainable, the courts seemed more sympathetic to restriction of withdrawals of water from the ground. At least this is one possible interpretation of the induced infiltration cases discussed in Chapter V, note 12 and accompanying text

17 "State laws should recognize and take account of the substantial interrelation of surface water and groundwater. Rights in both sources of supply should be integrated, and uses should be administered and managed conjunctively. There should not be separate codifications of surface water law and groundwater law; the law of the waters should be single, integrated body of jurisprudence." Recommendation No. 7-1, National Water Commission. **Water Policies for the Future**, (Washington 1973), at p. 233.

18. That is, landowners with property abutting surface watercourses.

Comprehensive Allocation

The Department of Public Health allocates groundwater supplies between competing municipalities and between municipalities and private users. As to competition exclusively among private users, the common law rule of capture would prevail. Under statute, the Department of Public Health "shall have general oversight and care of ..underground waters used by any...person in the commonwealth as sources of water supply..." This broad mandate has been exercised with restraint by the Department when the question of purely private use has been involved. The history leading up to the enactment of the statute granting this mandate concerned possible effects on certain public water supplies which private competing withdrawals would have. Furthermore, whereas the powers of the Department regarding protection and allocation of public water supplies are spelled out by statute in greater detail, the allocation of groundwater between purely private competitors is not implied under existing statutes beyond what can be gleaned from the wording of "general oversight and care".

The Department of Public Health does not now have a systematic program allocating groundwater among private users if municipal supplies are not affected by the competition. The fact that this is so does not mean that use of groundwater is substantially unregulated. The many hundreds of municipal sources which the Department regulates constitute a large segment of the groundwater use in the state. In addition, any private uses which might impinge on municipal uses can come under the scrutiny of the Department, if they are disclosed to the agency.

With regard to allocation of groundwater among private claimants, the cases provided in the previous chapters do not indicate the existence of persistent friction resulting from the common law regime. Of course, the failure of cases of hardship to come to light does not conclusively demonstrate that the system is functioning ideally. It may well be that well-owners suffering loss from competition by neighbors find that the common law cases are arrayed so overwhelmingly against them that court action is pointless.

Even in the absence of a clear showing of hardship stemming from the common law rule of capture, various factors indicate the wisdom of considering systematic regulation and allocation of private use of groundwater. Future demands on water resources of the state, if substantially increased over present usage, will place greater stress on existing supplies. If a rational system of apportionment is instituted before competition becomes acute, the results will be less intrusive than if the state intervenes when cutbacks and other forceful measures have become necessary. Furthermore, if maximum economic development is to be fostered consonant with wise multi-purpose use of water resources, it may be more desirable to be able to assure claimants a more certain right to fixed quantities of water. Presently, any private use of groundwater is subject to the threat of legally tolerated intrusion by new competitors; the right of "absolute ownership" may prove highly illusory to industries dependent on groundwater supplies.

It would be essential to integrate any new program purporting to allocate private groundwater claims with the present program maintained by the Department of Public Health. The Department of Public Health takes the position that its existing regulatory authority, reaffirmed by numerous legislative enactments and backed by

technical expertise and experience, should be preserved as part of its vital role in protecting public water supplies. However, to what degree the Department of Public Health should be required to decide allocation problems not clearly invoking public health issues is a troublesome question, particularly if one defines the issue of "public health" in its broadest context. Many of the problems to be determined by a system of allocation of groundwater among private users are related to the mandate of the Water Resources Commission. If the General Court chooses to consider a comprehensive system of groundwater allocation, we suggest that it would be desirable to consider the extremely important mandates which it has given both the Department of Public Health and the Water Resources Commission before deciding how to apportion the responsibility of administering a program of allocation.

If the legislature were to consider enactment of a comprehensive system allocating groundwater, considerable care would have to be given to selection of a program most suited for the needs of this state. Generally, recent thought has indicated that groundwater and surface water should be managed concurrently, with claims to the comsumptive use of the two integrated into a single permit program.[19] It is also frequently stated that rights to the use of water should be secure for a reasonable length of time in order to allow amortization of sunk costs which users incur in dependence on the water right.[20] An allocation system should have sufficient flexibility to allow new uses to supersede older ones if it becomes socially desirable for this to occur. Market transferability is one way of effecting this end. Constant reassessment of uses, as is possible under the riparian system of surface water allocation or a permit program with permits of limited duration, is another technique.

There are numerous methods of allocation possible. In Massachusetts now, that quantity of water which is in the groundwater phase of the hydrologic cycle is allocated on the basis of unregulated physical competition except for water in demand for public water supplies. If any water survives this competition, the remainder which discharges into surface bodies is allocated by the judicial principles of riparian and littoral rights among persons holding land on the shore of surface bodies. In most other Eastern states, the system of allocation is roughly the same, except that physical competition for groundwater is generally softened by judicial allocation on the basis of reasonableness.

Other techniques are possible. Rights to water can be rationed in firm quantities on a first-come-first-serve basis, with prior claimants having full protection as against junior claimants and no rights as against senior claimants. This is the system of prior appropriation as applied in the West and adopted for surface waters in 1956 in Mississippi. If voluntary transfer of the rights were permitted, economic theory suggests that the senior priorities would tend to gravitate toward the most valuable uses.

19 National Water Commission. **Water Policies for the Future**. (Washington. 1973) Recommendation No. 7-1. at p 233

20 Statutes in three states make this issue explicit by allowing permits for a period "necessary for reasonable amortization of the applicant's water withdrawal and water-using facilities." Ga. Code Ann. § 17-1107 (a) (3); Gen Stats. of N C. § 143-215.16(a)(iii); Code of Laws of S.C.. § 70-37(a)(iii)

Rights could be originally rationed on an auction market, thus allowing, from an economic perspective, a more rational distribution than that obtained by mere temporal priority. Such a system has not been put into effect in any state.

Rights could be rationed on the basis of priorities assigned to varying types of uses. A ranking of use categories would indicate the protection to be given to each type of use. As another possibility, instead of rigid categories of ranking, a system of ad hoc ranking of competing claimants on the basis of some general standard of social benefit could be made. Many state systems have some features of a ranking system, in that certain uses, such as municipal and domestic, are frequently given favored protection.

The common-law systems of water allocation exemplified by the present system of water rights in Massachusetts are generally considered to be a satisfactory method of solving the abrasiveness of conflicting demands when there is a general abundance of water. However, ad hoc determinations of reasonability made on a case-by-case basis may well break down if confronted with wholesale shortages. The real proof of a system of allocation is its effectiveness in dealing with shortage, and it is here that there is widespread suspicion about the effectiveness of the common-law systems. Numerous states confronted by gradually worsening competition for limited water supplies have over the years turned away from common-law systems to other methods of allocation. These include Oregon, Washington, the Dakotas, Iowa, Nebraska, and Kansas. The preponderance of states that have altered by statute the common-law scheme have chosen prior appropriation.

The doctrine of prior appropriation, born in the arid regions of the Southwest and intermountain West, was designed to cope with scarcity by giving prior claimants firm rights sufficient to induce economic development. In this regard it has been successful, although as the system has matured, certain deficiencies have become evident. For fear of losing part of his allotment, an appropriator is discouraged from making improvements in efficiency of use, because water saved by conservation measures is subtracted from his appropriation. A downstream senior appropriator can demand that water pass an upstream junior appropriator, even if large quantities of water will be lost to evaporation before the water reaches the senior user. Senior appropriations are often frozen into relatively unproductive uses, while more economically valuable uses are left unsatisfied. The system of prior appropriation requires a substantial administrative apparatus for its enforcement.

Nevertheless, many commentators feel that prior appropriation is the most rational water allocation system in use in the United States today, and that whatever deficiencies are found in the present working of appropriation systems can be rectified by relatively minor changes in practice. For example, the tendency of the system to protect inefficient uses of water could be countered by periodic re-evaluation of permits, with rewards for water conservation, perhaps by extending permits for a period of time proportionate to water saved. Of course, under such a system permits would need to be granted originally for uses which were efficient under then existing technology so that applicants would not apply for more water than they need, and then later show false conservation to obtain a permit extension.

Another significant body of opinion favors allocation by more flexible administrative standards. The National Conference of Commissioners on Uniform State Laws urges this technique in their Model Water Use Act, approved in 1958. Iowa, in 1957, and Minnesota, in 1937, adopted schemes of administrative allocation. Wisconsin and Maryland have rather limited permit systems, covering only certain types of uses.

The advantages of the administrative approach are that it gives both centralized management and flexibility. Unfortunately, the approach can also be burdensome and dictatorial and if not properly staffed can become perfunctory and meaningless. We do not yet have the example of an administrative system operating under the strain of sustained shortages to tell us the effectiveness of this approach under such conditions. One fact seems clear, however. An administrative system must have adequately precise standards to govern allocations; and the administration and enforcement systems must be adequately funded. For example, North Carolina, in 1951, enacted a permit scheme to be administered under the guidelines of "safety and public interest." The administrative agency grappling with this standard was inadequately funded and issued permits without hearings or field investigations. This unsatisfactory situation caused repeal of the permit program in 1961.[21]

Whatever scheme of water allocation were chosen, if it represented a change from the common-law system presently found in Massachusetts, there would occur some degree of encroachment on previously established property rights. The question necessarily arises whether such changes would be repugnant to the substantive due process standard of the Fourteenth Amendment of the U.S. Constitution, and similar provisions of the Massachusetts constitution, requiring compensation for public taking of private property. It would be helpful if there were a decision by the U.S. Supreme Court indicating the limits of the power of a state to alter rights to water. Though invited to consider this issue in **California Oregon Power Co. v Beaver Portland Cement Co.,** 295 U.S. 142, 55S. Ct.725 (1935), the Supreme Court declined to do so and chose to decide the controversy before it on other grounds. We are therefore relegated to the uncertain guidance of state supreme court decisions on the substantive due process point.

Statutes extinguishing or significantly modifying currently exercised rights to water have been found by several state courts to be constitutionally impermissible as a deprivation of property without due process of law.[22] In order to avoid this stumbling block, some legislatures chose to assert that only currently exercised rights to water constitute "vested" rights which are constitutionally protected. This at least allowed regulation of unexercised rights to water even though existing uses were preserved.

21 This history is recounted in Maloney, Plager, Baldwin, **Water Law and Administration; The Florida Experience,** (1968) p. 196. In 1967, North Carolina enacted new legislation regulating consumptive withdrawal only in "capacity use areas." North Carolina Gen Stats. sec. 143-215.11. **et seq.**

22. **Herminghaus v So. Calif, Edison Co.**, 200 Cal. 81, 852 P. 607 (1926); **Clark v Cambridge & Arapahoe Irr. & Improvement Co.**, 45 Neb. 798, 64 N.W. 239 (1895); **Huber v Merkel**, 117 Wis 355, 94 N.W. 354 (1903); **St. Germain Irr. Ditch Co. v Hawthorne Ditch Co.**, 32 S D 260, 143 N.W. 124 (1913); **City Mill Co. v Honolulu Sewer and Water Commission**, 30 Haw. 912 (1929).

Such schemes were held constitutional where challenged.[23] In addition, notwithstanding the older decisions finding unconstitutionality, several states have recently proceeded to enact permit programs which regulate both unexercised and existing uses of water.[24] This may be partially explainable on the assumption that the regulatory aims of the legislation could not be met without control of all uses, both old and new. It may well be also that developments in recent decades in the law of takings have indicated a point of view less restrained by legal categories than were the older cases.[25]

Although these brief comments far from resolve this difficult point of constitutional law, it seems prudent to proceed on the assumption that reasonable regulation at least of rights which are not now being exercised would be properly within the power of the state government. Even regulation of existing uses may at least be contemplated, in light of recent developments in the constitutional theory of the law of water rights.

The Option of Critical Area Management

Consumptive use regulation limited to watersheds identified as having critical problems is one technique by which several states have attempted to obtain the most important benefits of regulation in the most economical fashion. Both in states which have the Western doctrine of prior appropriation[26] as well as states with other forms of common law rules,[27] administrative agencies have been given power to declare critical areas and initiate special regulatory acctivity. In New York, there was a legislative determination that Long Island was a critical area, with the establishment of regulatory control in several counties there.[28]

In those states with critical area legislation, the normal formula, once a critical area is established, requires permits for new or significantly expanded uses. The time duration of these permits varies from state to state, with some statutes granting permanent or indefinite but revocable permits and some others issuing permits of limited duration. Some states, beyond curtailing new uses, also undertake to regulate existing uses if shortage or overdevelopment has occurred.

23 Knight v Grimes. 80 S. Dak 517 127 N.W. 2d 708 (1964): **Calif. Oregon Power Co. v Beaver Portland Cement Co.** 72 F. 2d 555 (9th cir. 1934) (aff d on other grounds. 295 U.S. 142): **Williams v City of Witchita** 190 Kan 317. 374 P 2d 578 (1962).

24 Mississippi. Iowa. Florida.

25 New theories. such as the 'diminution of value theory. first expounded in **Pennsylvania Coal Co. v Mahon** 260 S? Ct. 393 (1922) were developed to analyze intrusions on private property unheard of in the nineteenth century.

26 Nev Rev. Stats. § 534.110 **et seq.** Ore. Rev Stats. § 537.535 **et seq.** Wyo. Stats. § 41-121 **et seq.**

27 Cal Water Code § § 2100-2101 Haw Rev Stats. § 177-1. **et seq.** Ariz Rev. Stats § 45-301 **et seq.**; Ga Code Ann.. § 17-1101 **et seq.** Ind Stats Ann § 27-1301 **et seq.**; N J. stats. Ann § 58-4A-1 **et seq.**. N.C. Gen. Stats. § 1 :3-215. **et seq.**; S Carolina Code § 70-42 **et seq.**

28 McKinney's Consol. Laws of N Y Environmental Conservation Law § § 15-1525 through 15-1527.

The most substantial arguments in support of critical area regulation are those of administrative economy.[29] On the other hand, if users would tend to move to areas outside of the critical areas in order to avoid compliance with regulatory procedure, this would stimulate development of other critical areas. If the state must wait until trouble has developed in a region before undertaking regulation, it may be less free to plan desirable water-use patterns rationally. Some states try to forestall this problem by allowing regulation not only in areas where overdevelopment has occurred, but where it threatens to occur.

It may be desirable, if critical area management is the technique chosen, to give a new slant to this method by declaring the whole state subject to regulation, with exceptions of indefinite period for those areas administratively determined not to need regulation at the present. This would put future users on notice that regulation applies to all areas of the state and that it is only the relative abundance of water in some areas which makes more detailed regulation unnecessary.

Conservation of Water

To balance the constant search for new sources of supply to satisfy the increasing demand for water, it is time to recognize that better use could be made of our present water resources. Future planning should recognize the need for imposing social, economic and technological restraints on water demand and distribution. Some of the techniques which could be utilized are: reducing underground leakage in destribution systems, encouraging industrial recycling of water, installing water-saving plumbing fixtures, regulating use of water for lawn sprinkling and air conditioners, universal metering, regulating land use to be compatible with resource patterns, and encouraging use of treated waste-water and water which does not meet drinking water standards for appropriate uses (i.e., agriculture, toilet-flushing, etc.).[30] In addition, serious consideration should be given to revising water rate structures to reflect the stress placed upon public water supplies by high-consumption users. Steps such as these, when combined with a comprehensive program of public conservation education, would serve to maximize utilization of the Commonwealth's finite water resources.

Groundwater Pollution

Groundwater pollution is a troubling problem which has been the subject of increased public interest as of late. The urgency of this public concern within the Commonwealth has been underscored by the enactment in 1973 of statutes establishing a program of groundwater pollution abatement under the administration of the Division of Water Pollution Control[31] and a further program of control of road salt stockpiling under the administration of the Department of Public Health.[32]

29. In enacting a permit program, "States would be well advised to proceed on a basin-by-basin basis, applying the permit system to those areas experiencing the sharpest competition for water supply." National Water Commission, **Water Policies for the Future**, (Washington 1973) at p. 280.

30. Sheaffer and Zeizel, 1966, p. 141.

31. Chapter 546, Acts of 1973.

32. Chapter 1208, Acts of 1973.

These new programs have been in effect for so short a period that their effectiveness cannot yet be assessed. The problems of scientific study and enforcement are considerable, however; and these programs must be supported generously with funding and manpower to achieve their objectives properly.

Further research would be desirable in areas which have been the responsibility of the Department of Public Health for many years. These deal with the problem of septic system siting and pollution control. The judgment of proper placement of a septic system involves a compromise between the need to avoid noisome surface assumulations of septic waste and the need to avoid pollution of underground sources of water and related surface water systems. Research under the geologic conditions prevailing in Massachusetts as to the proper standards to reach in this compromise has not been thoroughly conducted. It would be desirable to support, with manpower and funds, the additional research and enforcement needed to keep these problems fully under control.

Land Use Policies for Recharge Zones

Water does not form naturally in the ground. Precipitation is the source from which aquifers are replenished.[33] This replenishment takes place by filtration through the soil in definable areas known as recharge zones. The protection of recharge zones is a land use problem which can have repercussions outside the political subdivision where the land use change takes place, because recharge zones do not necessarily stop at town lines.

Certain land-use controls which can be directed to the problems of recharge zones are now authorized by statute; but they may be inadequate to cope with the full problem.[34] Communities are now permitted to acquire, upon payment of compensation and with approval of the Department of Public Health, lands necessary to preserve the purity of public water supplies. This power does not seem directed to the issue of preserving a dependable long-term quantity by preventing land use changes which could interrupt recharge. Communities are also permitted to enact zoning regulations to facilitate adequate provision of water; but there may be little incentive for a community to restrict development in recharge zones within its boundaries which may be replenishing wells in neighboring towns. In addition, the general wording of the zoning enabling statute, even if it is intended to include zoning to protect recharge areas, may not be sufficiently precise to make clear the full extent of the powers granted.

As a long range goal, some sort of state-wide land use standards for recharge zones should be contemplated. In the short run, general enabling legislation should be enacted allowing towns to purchase or take critical recharge zones both within and outside town limits for

33. Bodies of surface water can also recharge aquifers, but, of course, the source of surface waters is also ultimately precipitation.

34. See generally the discussion of land use control in Chapter V. The National Water Commission has recommended public power to protect recharge zones. See Recommendation No. 7-5 and accompanying discussion in **Water Policies for the Future,** (Washington 1973) at p. 236.

the purposes of maintaining quantity as well as purity of municipal supplies. In addition, the general enabling legislation permitting municipal land use control should be amended to indicate clear legislative intent that recharge areas be protected by local land use regulation. Density restrictions, restrictions in structure size, required use of artificial recharge of runoffs from buildings and paved areas,[35] use of porous pavements if these are proven feasible, and any other restrictions appropriate to maintenance of the integrity of recharge areas should be urgently recommended.[36]

35. Assuming, of course, appropriate control of the quality of runoff water which is used for artificial recharge. See, for example, **Investigation of Porous Pavements for Urban Runoff Control**, U.S. Environmental Protection Agency, 1972 (11034 DUY 03/72).

36. The determination of which areas are recharge zones requires information and expertise. Considerable basic data is to be found in the files of the U.S.G.S. Studies which include designation of recharge areas have been performed for various municipalities by Dr. Dabney Caldwell and graduate students of Boston University.

GLOSSARY OF IMPORTANT HYDROLOGIC TERMS

Physical Properties of rocks and soils; The quantity of water available as ground water at any given location is largely determined by the physical properties of the rocks and soils in which it is confined.

1. **Porosity-** a measure of openness; more specifically, it is the amount of open space stated as a percentage of the total volume. A porous substance can hold more water than a non-porous substance because the latter has fewer openings available to be filled with water. On the whole, consolidated bedrock material is less porous than overlying, unconsolidated or partly consolidated deposits.

2. **Specific yield-** the volume of water that will drain from a sample by gravity, stated as a percentage of the gross volume of the sample. This is always less than porosity because some moisture is always retained as a thin film adhering to the surface of individual grains or cracks. As grain diameter decreases, the proportion of available surface area increases. For this reason more water adheres to small diameter (clay-sized) particles than adheres to larger diameter (sand-sized) particles, resulting in a larger specific yield from homogeneous samples of large diameter particles.

3. **Sorting-** a measure of the range of particles sizes from very small (clay, silt) to very large (pebbles, cobbles). The degree of sorting of grain sizes is an important determinant of the water-holding and water-transmitting characteristics of a soil sample. A wide range of grain sizes indicates that many of the pore spaces between large grains may be filled by small grains, which tend to restrict the storage and flow of water; such a sample is described as "poorly sorted." A narrow range of grain sizes, say primarily sand and gravel sized particles, indicates that many of the pore spaces between grains will remain open, facilitating the storage and flow of water, hence it is called "well sorted" or "uniformly sorted" in hydrologic terms. Civil engineers, seeking a wide range of particle sizes for good compaction, might describe a sample as "well graded" which an hydrologist would regard as "poorly sorted".

4. **Permeability-** a measure of the capacity of a material to transmit water through its interstices or open spaces. The coefficient of permeability is the rate of flow of water in gallons per day through a cross section of 1 square foot under a unit hydraulic gradient. Although all the pores of a substance may be filled with water, there can be no movement of water unless the pores are interconnected. It is readily apparent that movement is greatly facilitated by large pore spaces connected by straight pathways. The more tortuous a path and the smaller the pores, the more molecular forces apply and resistence to flow increases.

The following figure (Fig. A-1) shows the variations and orders of magnitude of permeability for laboratory samples of different-sized sedimentary materials.

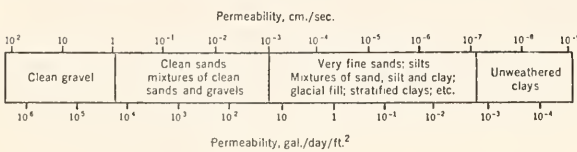


Figure A-1 Range in permeability of different sediment sizes (from Figure 2A, Hughes and others 1971)

5. **Transmissibility-** another measure of the capacity of a material to transmit water. The coefficient of transmissibility is the rate of flow of water, in gallons per day, through each vertical strip of the aquifer 1 foot wide having a height equal to the thickness of the aquifer and under a unit hydraulic gradient; it is equal to the coefficient of permeability multiplied by the saturated thickness of the aquifer.

Although many of these properties can be measured in a laboratory, the removal of a sample from the ground tends to disturb its natural relationships. For this reason modern groundwater studies rely primarily on field tests to determine the effective specific yield and transmissivity of an aquifer, or even more directly to determine the productive capacity of an aquifer by pumping tests.

It should be pointed out that there is a much greater possibility of finding a large supply of groundwater in unconsolidated deposits of sand and gravel than in relatively impervious bedrock where compaction due to compression closed the pore openings between grains. The only available openings in most consolidated deposits in Massachusetts are fractures, joints and faults, which tend to close with increasing depth.

Hydrologic Characteristics of Glacial Deposits; Although the history of the earth goes back for a period of about 4.5 billion years, only the past one million years need concern us. This is the period of earth history known as the great Ice Age (Pleistocene Epoch, in geologic terms), which has been marked by four major advances of continental glaciers separated by interglacial periods of ice recession. The most recent (Wisconsin) glaciation started about 100,000 years ago and ended in New England about 10,000 years ago. During this period all of New England, including Massachusetts, was covered by a solid sheet of ice much thicker than the highest mountain found today anywhere in this region.

The advancing ice moved huge boulders great distances, scoured hills and valleys of their soil down to bedrock, and completely altered the previous landscape. As the ice cap began to melt, water from the melting glaciers transported, sorted and deposited rocks and sediments which previously had been frozen into the glacier. At its maximum the area of glaciation extended as far south as Nantucket, Martha's Vineyard, Block Island and Long Island. As it retreated it left an irregular ridge of unconsolidated deposits, called a terminal moraine, marking its farthest advance. Meltwater issuing from the front of the retreating glacier, created gently undulating outwash plains of sand and gravel. Old valleys were filled with glacial deposits; glacial lakes formed when meltwater accumulated in newly formed basins. New drainage patterns were established. A thin veneer of till (ground moraine) was deposited over the landscape, but the passage of the last glacier also left many exposures of bedrock.

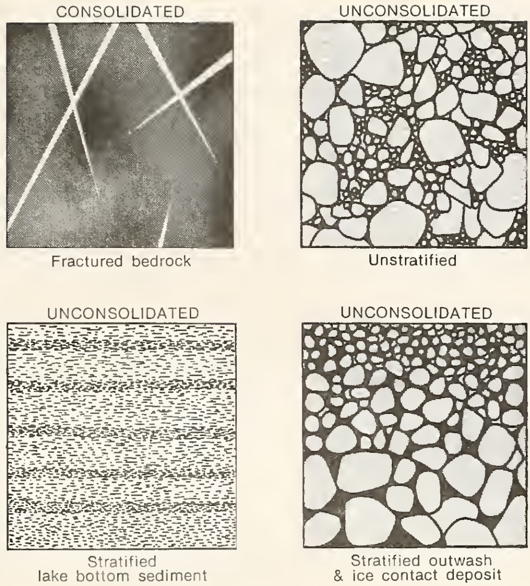


Figure A-2

Consolidated & Unconsolidated Deposits

The reworked landscape consists of four types of material of interest to us because of their strikingly different hydrologic characteristics: (Figure A-2)

(1) **Fractured Consolidated Bedrock–** These are largely the rocks making up the surficial portion of the crust of the earth. Because the fractures tend to narrow with increasing depth, porosity and permeability are both poor. On the whole wells drilled into bedrock will provide an adequate supply of water for private use but not for large-scale, public purposes. Also, because pollution may travel considerable distances through cracks and fissures, wells drilled into bedrock are not encouraged in Massachusetts.

(2) **Unconsolidated, unstratified deposits (till)-** Till is a collection of poorly sorted rock fragments ranging from boulders to clay-sized particles, deposited randomly over the landscape directly from glacial ice. Because of its low porosity and low permeability, this material generally furnishes only enough water for domestic purposes and is rarely tapped for water supply with modern well construction techniques.

(3) **Unconsolidated, stratified deposits (lake-bottom sediments)–** Lacustrine deposits consist of stratified layers of fine sand silt and clay deposited in the bottoms of lakes formed by glacial meltwaters. Such deposits have high porosity but low permeability and low specific yield, indicating that, although they can hold much water, their water retention is so great that they are unsuitable as a source of water supply for municipal purpose.

(4) **Unconsolidated, stratified deposits (outwash and ice contact)–** Well-sorted coarse sands and gravels deposited by glacial streams and fluvial meltwaters have in general high porosity, high permeability and high specific yield. This is the most suitable material in which to locate large municipal supply wells with the most reliable characteristics. Water saturated thickness is important to aquifer yield. As the proportion of sand and finer particles in these deposits increases, permeability decreases. Ice contact deposits tend to have a larger proportion of coarse sediments, but these may not always be as well sorted.

Other Hydrologic Terms:

1. **Safe Yield–** "Safe yield of an aquifier is the practicable rate of withdrawing water perennially. Safe yield is an idea only. It does not exist. It can be neither measured nor expressed quantitatively and correctly." (**Water Supply Engineering;** Babbitt, Doland, Cleasby, 1970 p. 21)

The rate at which water can be withdrawn from an aquifer without depleting the supply to such an extent that withdrawal at this rate is harmful to the aquifer itself, or to the quality of the water or is no longer economically feasible (Meinzer, 1923, p. 55).

Properly applied the concept of safe yield can be a useful tool.

2. **Consumptive use;** That portion of the total quantity of water withdrawn and used by man which is not returned as recharge to the groundwater system at a location where it will compensate for water withdrawal. It is generally stated as a percentage of the total quantity of water withdrawn.

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